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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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The Man-Machine Interface in Tactical Aircraft Design and Combat Automation

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AGARD Conference Proceedings No.425

THE MAN-MACHINE INTERFACE IN TACTICAL AIRCRAFT DESIGN AND COMBAT AUTOMATION

Papers presented at the Joint GCP/FMP Symposium, held in Stuttgart, Germany from 28 September to 1 October 1987.

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PREFACE

Technological advances have made possible the development of system capabilities which allow more effective weapon system operation under difficult conditions, such as low altitude, high speed, night and all weather. Higher levels of technology integration and combat automation are now becoming essential to enable the pilot to accomplish the critical functions of flight path control, threat management, navigation, attack engagement and weapon system management. Furthermore, weapon delivery and survivability are expected to face further challenges from the complex threat environment predicted for the 1990s.

Several emerging technologies are now beginning to spawn major innovations in aircraft design, through the use of combat automation concepts. These technologies carry significant implications in respect of pilot workload, situational awareness, crew station controls and displays, and automated system functions including integrity management. Effective and efficient harmonisation of this total weapon system, which must also achieve the essential features of pilot acceptability and safety, is critically dependent on the pilot/vehicle interface. This symposium sought to address these critical issues of combat automation and the man-machine interface. In particular, it considered the major implications and trade-offs involved in varying levels of airframe and weapon systems sophistication and such fundamental choices as that of single seat versus two seat operation.

* * *

Les progrès technologiques ont rendu possible le développement de systèmes capables de rendre plus efficace la mise en oeuvre d'un système d'armes des conditions difficiles telles que basse altitude, grande vitesse, utilisation de nuit et tous temps. Des niveaux supérieurs d'intégration technologique et d'automatisation du combat deviennent désormais essentiels pour permettre au pilote d'accomplir les délicates fonctions de contrôle de la trajectoire de vol, la gestion de la menace, la navigation, l'engagement du combat et la gestion du système d'armes. Plus encore, le largage des armements et la survivabilité affronteront davantage de défis dans l'environnement complexe de la menace prévue dans les années 1990.

L'émergence de plusieurs technologies commencent à multiplier les innovations majeures dans la conception des aéronefs grace aux concepts d'automatisation. Il s'agit plus particulièrement des systèmes numériques de bases de données de la topographie, la commande vocale, l'affichage sur le casque, la commande integrée de vol et de tir, l'assemblage du capteur multifunction, les stratégies de reconfiguration et de prise en compte de l'erreur ainsi que des systèmes experts. De telles facilités entraînent des implications significatives concernant la charge de travail du pilote, la prise en compte des situations, l'affichage et les commandes du poste d'équipage et les fonctions automatisées y compris la gestion de son integrité.

L'harmonisation effective et éfficace de ce système d'armes global qui doit aussi satisfaire les normes essentielles de la sécurité et de l'acceptabilité du pilote est réellement dépendante de la relation homme/machine.

Ce symposium s'est efforcé d'aborder les problèmes critiques de la relation combat automatisé/homme-machine. Il a examiné notamment les implications majeurs et les bilans qui interviennent aux différents niveaux de sophistication de la cellule et des systèmes d'armes et des choix aussi fondamentaux que le monoplace opposé au biplace.

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MAN-MACHINE INTERFACE - OPERATOR'S VIEWPOINT

by
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SUMMARY

Man is the complex variable in the man-machine equation. Already his limitations are influencing aircraft design.

As the reach, accuracy and lethality of modern weapons increases, air combat will become ever more complex and gladiatorial. With such a hostile environment, the man in the cockpit will have to be confronted with only the best tactical information and concerned only with how best to engage the enemy; many of the subsidiary tasks, such as managing the aircraft systems, need to be undertaken automatically.

Reliability and maintainability have a great influence on the effective ratio of forces and will become increasingly important in the years ahead. Similarly, new systems should be designed in their entirety for operations in a hostile chemical and electronic environment.

It is a great pleasure and an honour to be invited to give the Keynote Address at this AGARD Symposium, and to start off your week's deliberations. Particularly so because my association with AGARD in the past has proved so stimulating and has allowed me to meet a group of dedicated engineers and scientists who are specialists in fields quite different to my own. For I address you today as an 'operator', not as an engineer. I am the 'man' in your 'man-machine' interface.

'Man-machine' interface has become a buzz-phrase and it may be appropriate to start the week's proceedings with at least a quick examination of it. It rates with 'cost-effectiveness' as one of these frequently misused combinations. Scarcely a week passes without someone using 'cost-effectiveness' as a synonym for 'cheap', or alternatively using it to justify some piece of equipment which patently does not work. Yet it is neither of these things. A 'megabuck' piece of equipment which does something is still 'cost-effective' compared to a cheap piece of equipment which achieves nothing. So it is with 'man-machine' interface - it is the sum of the parts and we must be ware of being so fascinated by one that we forget, or deliberately ignore, the other.

There is a strange contradiction in our man-machine combination. One part - the machine - obeys laws and can be explained by formulae. The other part - man - follows few such logical laws, indeed he can be annoyingly unpredictable. He is not even constant - they are all a combination of idiosyncracies, prejudices, likes and dislikes; they do not even come in the same shapes and sizes, and their performance defies any reliable measure. You might be excused for complaining that if God did indeed create man, then he was certainly not a qualified engineer.

The men who fly aircraft are generally drawn from the physically fit and the moderately intelligent. In a number of western countries the demands placed upon intelligence are high-degree standard in many cases. Yet as demographic trends start to bite, and as industry places its legitimate, and welcome, demands on the graduate market, the military may have to take second place, not only on the basis of supply and demand, but as a matter of policy in the national interest. It may take such pressures to make us ask ourselves why great academic capability is necessary to fly and to fight an aircraft effectively? Maybe it is needed to produce a future career officer, but it is difficult to justify as a necessity for flying an aircraft. Give me a 16-year-old who urgently wants to fly fighters - and who can ride a bicycle - and I will produce a passable fighter pilot. Great academic ability is not a pre-requisite for a combat pilot as so many of the 'aces' of the past proved so convincingly.

Physical fitness certainly is a requirement and we have probably reached the point where the curves cross. We have aircraft able to penetrate at 600 knots and above and which handle well enough to be flown at those speeds down to about 100 feet. But not too many pilots can fly an aircraft - and use it - much better than 600 knots and 100 feet; maybe the odd von Richthofen-clone but not the crowd. The nine 'G' aircraft is also upon us and already 'G'-induced-loss-of-consciousness is raising its ugly head as the two F-20, and possibly the Hawk 200, accidents showed so tragically. Yet there is no reason why the designer should stop at nine 'G' - the missile, after all, pulls 40 'G' or more - but he is artificially constrained while he has to keep the man in the loop. So one of the first questions to pose - at least in some of the roles - is why worry about man-machine interface; why not just remove the man?

Taking one step back from that precipice, let us look at the modern combat scene. The first thing which should be borne in mind is its great lethality. It always has been lethal and a look at some of the experiences of the World War Two 'Experten' puts the point. Erich Rudorffer's kill rates on a number of occasions: eight aircraft downed in 32 minutes, seven in 20 minutes 13 in 17 minutes. Emil Lang who killed 18 in one day closely followed by Marsielle with 17 in one day. Hans Hahn who killed 40 aircraft in only seven missions. All this was with fixed forward firing guns and cannon. Now, not only has the close-in combat missile entered the equation - and missiles make 'aces' of those who gunnery would have weeded out - but the Beyond-Visual-Range (BVR) battle must be won, or at least 'survived' before the classic high-'G' dogfight is entered.

This extension of the field of battle out into BVR ranges has put a new imperative on 'situational awareness' - another buzz-phrase - but translated, means 'what-on-earth-is-going-on'. If the AIM-54 Phoenix is to be our par then the area of interest starts as much as 100 nautical miles ahead of the nose and that is a lot of sky, particularly in northwest Europe where on day one of World War Three there are going to be many thousands of sorties flown.

These ranges are, of course, way beyond visual perception and our situational awareness is going to be dependent upon help from sensors. Raw sensor input would be enough to swamp our inadequate human operator and the information may have to be processed and then fed to him, carefully, in brain-sized chunks of digestible information. And now we start to toy with what man-machine interface is all about. In the modern cockpit there is going to be DATA DELUGE - and there needs to be - but how can we use it and understand it?

So, what is this new data deluge? What causes it? System complexity has something to do with it and the difference is vast between an F-15 or Foxhound on the one hand and a World War One Fokker on the other. But we must not get so fascinated with the system complexities that we forget the tactical complexity, for technology has added so much to this area that it could become the dominant problem.

For a moment consider what aviation in its short history has done to the 'minute'. In World War One, two fighters, heading for each other, would cover just four miles. By the start of World War Two that had become 10 miles. By Korea, a step increase to 17 miles and today, 38 miles. Now also, we have both 'look' and 'reach' to match these new 'minutes', indeed far more than one minute. Phoenix has hit in test in excess of 100 nautical miles - modern radar, particularly the big ones in the larger fighters, will have 'look' into this region - well beyond visual range.

Such weapon system performance, in both 'look' and 'reach', has increased the area of vulnerability by some orders compared to that applicable to the fixed cannon armament. Consider just how much. An aircraft could be vulnerable from a Phoenix-type of missile - from all aspects - over an area of nearly 39,000 square kilometres. In the early stages of a NWE war there could be well over 100 aircraft in that area - on average - and considerably more during periods of concentrated operations. So when we congratulate ourselves on our new generation radars with track-while-scan on 20-or-so targets we need not to be too self-satisfied. It still only scratches the potential problem, a problem made immeasurably more complex by the lack of an effective identification system.

Putting our eyes in the cockpit may not be a healthy thing to do. History has something to say about that. One study shows that 80% of aircraft killed in combat did not see their attacker. Another showed that 70% of aircraft shot down had less than 30 degrees of bank on when hit. The Soviets believe that of those aircraft killed by unseen assailants, 73% fell to opponents coming from the vertical plane. It is easy enough to imagine combats, head-in-cockpit, against a single opponent but this will probably be the unlikely event. Multi-aircraft combats are much more likely to be the norm and that makes enormous demands on both situational awareness outside the cockpit, and system or sensor interpretation inside the cockpit.

This is a real problem. To come alongside an aircraft after creeping up behind unseen to find that the pilot, in his 360-degree vision cockpit, is flying along, his head bowed studying all those expensive devices designed to keep him alive, oblivious to your presence, initially is amusing - then it is sad - then it is worrying.

Some argue that the answer is to split the load and to use the two-man crew. Up to now there have been good performance reasons for retaining a single-seat design if possible. Fuel, weight, added complexity and thereby less performance. Now, when we are at the point of nine 'G' aircraft, maybe a performance penalty is no longer a necessary price to pay. Perhaps the factor arguing against the multi-crew aircraft now is manpower costs - costs both financial and in terms of recruiting and retaining sufficient high quality people.

Come with me through some first order mathematics that would be applicable to my own service. The average length of aircrew service in the Royal Air Force is 18.3 years of which about one-third would be spent on the front line. A couple of years ago it was estimated that it cost about 1.6 million pounds to train a navigator. Take a force of 100 aircraft manned at an aircrew-to-aircraft ratio of 1.5-to-1, therefore requiring an on-line force of 150 navigators. Over a 20-year life we need 3000 navigator-man-years and we get just over six years front-line service out of a navigator. The answer comes out to the need for 491 navigators to make our aircraft two-place.

Amortising training cost and pay and pensions we find that the premium we pay for two-place could buy another 27.5% of aircraft at 20 million pounds each. That is an impressive premium to pay for a two-place solution.

If we costed things properly - not that we do, but if we did - that would give you working in man-machine interface a handsome budget to solve the problem of information handling short of the two-man answer. You may have to try anyway - already we have NATO air forces unable to man their aircraft even to a 1-to-1 aircrew-to-aircraft ratio and airline recruiting has yet to reach its peak, and European economies are still to emerge fully from the recent depression. Such are the imperatives.

So how do we - more correctly, you - go about doing it? Let me give you an operator's viewpoint.

In my travels around industry - and my previous exposure to AGARD - I am impressed at the quality of our engineers, scientists and designers. But I have sympathy with them, because knowing what is required in the cockpit of a combat aircraft if you have never been there is difficult, some may suggest approaching the impossible. Whatever may be said for the specifications written by operational requirements staffs, the last thing that could be said for them is that they transmit the 'flavour' of the environment. Yet I have also been around the operators on the squadrons, and a very splendid group of young men they are too. But, how often do we get them together? Too often what we think is 'liaison' or 'rapport' between the services and industry turns out to be the expense account lunch between the Generals and Air Marshals and the Managing Director. I accept that as part of 'life's-rich-panoply', but it is not the forum where some bright designer is going to hear of an operational problem and cry 'Eureka'. That is more likely to happen over a barrel of beer or some chipped coffee cups. So my first suggestion is to get the young men talking together. Do not forget how the Manchester became the Lancaster - the designers went to talk to the operators in the field and vice versa. There was not a little of the same thing happening during the Falklands when no British aircraft went to war unmodified in some way or the other. Must we wait until someone shoots at us first? Of course not - we just need to get the act together.

Whereas we can improve the 'machine' part of our interface these days by adding boards or chips, we have less scope with the 'man'. Here we are limited by the Lord's somewhat dated design and if we are to put a great deal more information into the man, *we first need to make room for it - we must reduce the load commensurately elsewhere.* Where?

The difficult part of air operations should be the 'operations' but not the 'flying' of the aircraft. Yet currently, flying the aircraft, and managing the systems, takes up just too much time. In many respects the man is used merely as a servo-mechanism and that, these days, is a waste. Consider a typical task. A light comes on to warn, say, of low fuel pressure - the pilot refers to Flight Reference Cards (if he is of the new school) which tell him that he throws a fuel cross feed switch and places another booster pump on line. Meanwhile his head - and more important, his attention - is in the cockpit. But why? Why does not that original sensor throw the other two switches - more correctly, make the circuits - without bothering the pilot at all? Why do we have, in the 'electric aircraft', lengthy take-off checklists requiring hands to flash about the cockpit during a scramble? Where is the one switch marked 'TAKE OFF' which sets up the aircraft for take-off?

In current aircraft there are far too many demands on the pilot's attention mainly due to bad design - or am I being too cruel there - let us say 'thoughtless' design. Just take three examples: a design in which the engines can quietly go into silent-surge resulting in the aircraft shelter floor having to be swept clean - literally - of buckets full of turbine blades. Another in which an electrical failure can cause the engines to overspeed to destruction - sorting out the electrical problem is not helped by the engine turbine discs sawing off your tailplane! Yet another whose computer control laws so prevented an overstress that pilots could not overstress even to avoid hitting the ground. This sort of design makes the human servo-motor spend too much of his limited intelligence worrying about things which are 'flight' critical rather than 'mission' critical. So, one of your early steps should be to unload the 'man' bit from much of its present unnecessary system management load.

Then we come more to the crux of the matter - the cockpit, or 'office'. If industrial firms provided an environment for their workers anything like some cockpits, there would be strikes and prosecutions. Indeed, if only some animal rights organisations would make pets of pilots! But generally this is an area of progressively good news and just a little danger.

The good news is that the day of the ergonomic slum seems to be over - at least in the west, even if it remains enshrined in aircraft such as the Flogger. The slight danger is that our efforts to improve the cockpit do not go too far. Glass cockpits, multi-function displays, head-up displays and the like are all excellent in their own right but we must be careful. We are not talking of airliners in their benign operating conditions. Combat aircraft live a hard life and must be resilient to it. The cockpit environment has to be looked at not as a series of individual systems crowded into a small place, but as an integrated system. As engineers you may justifiably say "tell me something new". But the difference between your good intentions and my front-line cockpit is a mass of committees, financial parsimony and lowest common denominators.

We tend to get a 'consensus cockpit' and that tends to satisfy only 'consensus-man' - and he does not exist. Man is a remarkably adaptable creature - after the first sortie he will complain loud and long - after the fifth he takes it as the natural order of things - he has 're-programmed' himself. He can adapt reasonably easily to the black or the white, but will complain for years about the greys which are neither one thing nor the other. So, a danger in your business of man-machine interface is the 'multi-pilot-cockpit-committee'.

What we incorporate as new technology in our cockpits, however, must be that which is needed to be there not that which could be there. We must watch for technological 'circus tricks' or project manager 'ego-trips'. Let me give you a few examples of those circus tricks which cause me some disquiet.

Let us start with digitalisation. Because we can show things as figures, we do so; hence, our head-up displays are full of them. And if I was an airline pilot - perish the thought - I would have no argument with the trend. But how do I get RATE out of a digital read-out? If I am flying an aircraft which can go up - or down - by tens of thousands of feet a minute, a digital read-out of altitude is little more than a meaningless blur; for that I need an analogue presentation. In a fighter-bomber - which will remain nameless only to protect the guilty - we have a digital fuel presentation; however, not in one single gauge but in three. To find out your fuel state you have to read three gauges - then add them up. At 600 knots and 100 feet with a MIG on your tail, that is the sort of hassle you could do without. An older - and less expensive aircraft - had two big clock-like fuel gauges. You didn't have to 'read' them; if the needles were better than 11 o'clock you were all right - nine o'clock you wanted to know where you were landing - eight o'clock was the last circuit. One quick glance told you your fuel state - no need for the exercise in mental gymnastics.

Hands-on-Throttle-and-Stick (HOTAS) must be the norm rather than the unusual in any aircraft capable of more than a sustained six 'G'. Cockpit designers ought to have a couple of trips in a centrifuge as a matter of essential education. A nine 'G' arm is effectively unusable unless it is supported.

A development which does worry me is the fascination with voice-operated controls. Again, I have no argument about it in a Boeing 747 - although why they need voice-operated controls when they have 16 stewardesses is beyond me - but in combat how do I programme the computer to recognise, not my steely-eyed crewroom voice, but my hysterical seventh-octave garble when I have spotted the SAM missile heading my way? We must also be very clear as to what exactly is a legitimate command. Fighter pilots under the stress of combat and high 'G' are renowned for their immoderate, if not even coarse, language and if in a moment of crisis they use certain expletives, there must be a way of telling the computer that they don't mean it to be executed literally!

We have a long way to go with colour. It is said that a picture is worth a thousand words. Recent studies have proved that it is worth much more. Colour can make a picture worth even more again and its use in two ways immediately springs to mind. The obvious use - to indicate friendly as green, hostile as red, or unidentified as yellow - can be useful particularly when a complex air situation has to be indicated. Less popular, perhaps only because we have given insufficient thought to it, is the use of colour to indicate the timeliness of information. A plot of a target derived from memory or from prediction needs to indicate how old is the hard evidence of position. Changing the colour of the presentation according to its age can be an excellent use of colour and can save the man - the operator - a considerable amount of mental anguish.

In combat aircraft we have already seen that keeping eyes out of the cockpit is vital. The head-up display is a big step in the right direction - a very good step at that - but a 'step' nonetheless. Although the new holographic HUDS have much increased the field of view, HUDS remain fundamentally forward-looking devices. In combat, as close to a 360-degree view as is possible is required. Two information flows are required: the first, feeding data on targets into the weapon system and the second, feeding data from the weapon system to the pilot. The answer, at least in the immediate future, seems to be Helmet Mounted Sights (HMS). It is a matter of amazement that so little emphasis has been placed by the requirement community on HMS when they are quite happy to contemplate agile missiles with capabilities some way beyond the gimbal limits of radars. One would seem to go with the other.

This is not to say that there are not problems. Putting further weight onto already heavy helmets, which have to hold other devices, like Night Vision Goggles, then having it all survive an ejection, is asking a lot.

But let us not be so tunnel-visioned on man's primary sensor - the eyes - to the detriment of the ears. When you are looking 'over-the-shoulder', aural messages, in the form of bells, whistles, horns or whatever, have a lot to offer. Be careful with voice warnings. There can be a lot of radio traffic in a combat situation and it must not be blocked by some seductive voice telling you that the cockpit temperature is high.

Let me mention three practical engineering points of great concern to the operational commanders.

The first of these are the so-called 'ILITIES' - Reliability and Maintainability. I have sympathy with designers who have to battle for funds at the early stages of projects, with accountants who are more interested in short-term rather than long-term budgets. Life-cycle-costs have weighed too little in the consideration of projects at this early stage. As manpower becomes scarce, training more expensive, and amortisation more important, the reliability and maintainability factor will carry more weight. In my own Ministry of Defence, life-cycle-costs are being talked about more seriously than ever before and I am encouraged by that, but I sense that we shall have to travel through the 'realisation-gap' where it will be unreasonably expected that reliability and maintainability will be produced by exhortation rather than by conscious investment.

Let me give you just two examples of why R and M is vital. We already have in NATO aircraft which can be operated on very long missions as we capitalise on the heavy investment in air-to-air refueling. The operational pay-off of such operations can be enormous, allowing our numerical inferiority against the Warsaw Pact to be partially offset. But how much sense does it make when an air-to-air refuelled mission time can be three times the mean time between failure of the primary operational sensor? Again we return to the necessity of looking at our investment decisions from a total system viewpoint rather than in slices of the problem. Easy to say, difficult to do, and impossible to start with a clean sheet of paper.

The other importance of R and M also falls from our numerical inferiority. We start the northwest European air war about 2 to 1 down on the Warsaw Pact. It is vitally important for us to optimise sortie rate in the first couple of days - and nights - of operation. With disrupted bases, casualties amongst our technicians, our clean-air avionics workshops with holes in them, and everyone looking at their thick neoprene gloves through their respirators, that is no time to find that your servicing manual calls for tweezers and micrometers. Whatever wonder mechanism is the light of your life, therefore, Gentlemen, IT HAS TO STAY ON-LINE.

You may wish to ponder whether you should go for high technology for its own sake. Some time ago a piece of Soviet equipment fell into western hands. It caused amusement amongst western technicians because of its rough and rude, indeed old-fashioned, design. Their smiles were fixed by the time it failed on test after some 600 hours - our western high-tech version had an MTBF of a little over 25 hours. We have already been through the lesson - keep the circus tricks and the technological ego-trips for the airlines. If the 'warplanes' break, we lose more than profits. The military do not want 'aeroplanes' - they need 'warplanes'. If the other side's 'warplanes' allow them just a 10% better availability than our own, and they can keep them on line for just one more sortie per day than we can, then our numerical inferiority has just gone from 1 to 2 down to 1 to 3 down in terms of practical air operations. The highest pay-off in practice could be putting hi-tech to work on the 'ILITIES'.

The second of my final points is somewhat along the same lines. When you design your 'man-machine' wonder kit, ask yourself how it will be able to be serviced in a chemical environment. Easy, take it out of the chemical environment. But what use is that if you have cooled it by forced air ventilation? You could have persistent chemical all over your boards and chips. It is too convenient to neglect the chemical threat. But the Soviets have 300,000 tons of the stuff; it has been used in the IRAN/IRAQ war; it caused thousands of casualties in World War One and, even then, it was not new. In 1482 the Commander CORIBUT, during the seige of Carolstein, had 2000 cartloads of dung catapulted into the town to spread disease and pestilence. And, as an aside, just check that the latest penetrative chemical agents will not ruin the insulation on your microcircuits.

Happily, micro-electronics do not produce as much heat, and do not need as much forced-air cooling as did older equipment. But that brings me to my third and last concern, Electro-Magnetic Pulse. We are all aware of EMP as a by-product of the nuclear explosion, but - let us be honest - how seriously do we take it? After all, if the primary defence policy of the west is to use the nuclear weapon as a deterrent, that is, to make war unthinkable - by either side - then one cannot be too hard on designers who do not take EMP vulnerability as seriously as they might. But, the Soviet press are now quoting, verbatim, long passages from the American press on non-nuclear EMP, that is, the means of producing EMP by conventional means. Western scientists, on the other hand, claim that their interest in the subject has been sparked by scientific articles published openly by the Soviets. We might expect a little sparing about this sort of thing but the prudent parent of a new 'man-machine interface' idea might be well advised to make the case out of lead and not to connect them all together with wire - or should we say in this environment - aerials.

So, in sum, what is my operator message. The combat pilot is faced with data deluge which, in an increasingly lethal air environment, is essential to his survival - but only if he can absorb it. It is going to require a close partnership between the operator and the designer if success is to go to the side of the angels. But let us not spend too long talking about it. For those who have not noticed, the great technological lead with which we have reassured ourselves over the last 30 years is rapidly being eaten away, indeed, in some areas has long since gone. We can, however, afford another week - and I wish you all an enjoyable symposium here at AGARD in Stuttgart and hope that someone will go away as a result and eventually cry - 'EUREKA'.

Mission Planning and Proper Design: The Long Range Connection

by

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SUMMARY

Mission planning in tactical fighter operations is as important today with our highly integrated, software intensive aircraft as it was in any tactical operations of the past. As we move into the next *generation, its importance will grow--not diminish. The mission planner's task, whether performed* by a pilot or a systems operator, can be made easier and less susceptible to errors if designers understand the planners task and design to both move the workload to the planning room and minimize planning by proper choice of operational modes and aircraft sensors.

There is a special connection between planning requirements and the design of the avionics suite to include its cockpit layout in a tactical fighter. However, this relationship should not be a simple function; that is, we do not wish to see cockpit workload decrease at the expense of ever increasing preflight workload. The move should always be to design cockpits and avionics suites that move as many functions as possible to the preflight planning room thus easing the pilots inflight duties and allowing him to focus his attention on flying his craft and keeping abreast of the tactical situation. But a corollary to this move is one to design cockpits with operational modes and sensors which will reduce the time needed to plan a mission, thus reducing reaction time for our tactical forces.

This paper is simply one man's opinion of the importance of mission planning, now and in the future. This opinion has been formed over 22-years of flying a wide variety of tactical fighters, running the gamut of tactical operations. Most of this paper is spent on what I believe is the key to both successful mission planning and successful mission execution--proper cockpit design.

MISSION PLANNING: KEY TO SUCCESS

The image of the role of mission planning in modern warfare that prevails in the minds of many people is more akin to what they have seen in movies like "Star Wars" than the actual case. They see fighter pilots scurrying to their aircraft with seemingly no preflight planning save for a quick game plan and pep *talk briefing prior to entry into a battle against a complex and formidable enemy.* Maybe someday--but not today. Mission planning is even more important to today's fighter pilot than it was to those first aviators who took the battle airborne in World War I and its importance is expanding--not contracting.

In the dawn of airpower, the fighter pilot required little more than a clear day and a road map. His planning was simple--a few lines drawn on the map, pinpointing of known enemy defenses, fuel usage computations, and target area study. His most difficult planning task was to "visualize" how map features would appear in three dimensions. His craft was well matched to this simple planning, having a speed that allowed his mind to easily keep pace with the mission and a display (the real world) which required no new interpretive skills. As simple as his mission planning seems, failure to accomplish this planning doomed the pilot to entering the battle with little or no situational awareness. Success without proper planning was doubtful.

Employing the next generation of fighter aircraft will require even more detailed planning than what we have seen in recent times. The aerodymnamic efficiencies of the present and future aircraft coupled with improved performance engines allow tactical fighters to cover longer distances. A low-level mission may easily require 20 to 30 steerpoints which have to be chosen and programmed into the inertial navigation system. Sophisticated enemy defenses must be studied and the decision made whether to avoid them or attempt to defeat them.

As the missions of fighter aircraft have expanded, the dependence on human vision has decreased, being displaced by radar and infrared devices. Such systems allow visibility beyond the capabilities of human vision, but require an extra step in premission planning. Where our World War I pilots had to visualize how map features would appear in the real world, pilots using radar and infrared sensors must first determine which features will even be displayed and then predict how they will appear. In the case of radar systems, the axis of attack becomes extremely important because a target which may be an easy to find radar target from one direction, may be totally invisible from another. The advent of synthetic aperture radars has helped significantly *in radar interpretation,* but *has added new dimensions* to the planning task such as the requirement for off-axis approaches, that is, not flying directly to the target while obtaining the radar map. Infrared systems are very much time of day and weather dependent. Pilots employing these systems must be aware of possible thermal crossover, the point at which an object either becomes colder or hotter than its background. High absolute humidity significantly degrades the range of an infrared sensor and thus affects the type of targets and turnpoints the pilot should plan to use. Additionally, whereas the World War I pilot had virtually unlimited visibility, pilots using radar and infrared sensors look at the world through a window which can only be correctly used if detailed planning precedes the mission. Weather conditions being one of the most unpredictable planning factors, pilots must prepare for the worst, but be able to take advantage of improved conditions. This is especially true in night operations where both poor weather operations using radar and clear weather or under-the-weather operations using infrared sensors require significant display prediction.

As the number of sensors available to the pilot grows, the mission planner is faced with a matrix of trade-offs which must be considered as planning for one system affects another. Mission success will be dependent on making the right compromises which allow for near optimal use of several systems, thus allowing them to compliment each other. Failure to do this may doom the mission to failure due to an over dependence on one system vice another. For example, consider the pilot who plans a mission using only his infrared sensor without considering radar predictions in the target area. If he arrives at the target shortly after a rain shower, he would see nothing of infrared significance on his IR display, but his radar display might have several strong returns any of which could be his target. Alas, at 500 knots too little time exists to make sense of the radar display without premission planning. Thus, it is clear that proper mission planning considering all available information remains an essential ingredient to mission success.

DESIGN FOR SUCCESS

As our world gets more complex, inventors have come up with a plethora of labor saving devices which populate our homes and work places. As many of us have learned, however, these devices can become our masters if not properly integrated and controlled to allow life to go on as we want it. So it can be with the present and projected tools of the air battle. Choosing the right systems and designing them with the operator in mind, will not only reduce his inflight and preflight workload, but allow him to remain master of his machine.

The Right System

The ideal situation for the air battle commander would be to have specialized weapon systems operated by specially trained crews for each type of mission. Each aircraft would be less expensive than a multirole system because of its limited capability. His pilots would be experts in their mission because they would only have to train for one type of mission. Of course, this ideal force presupposes crystal ball knowledge on the part of the commander. If his look into future requirements turned out to be less than totally accurate, he could well find himself with a ground attack force which could not prosecute the air-to-ground battle because he had misjudged the size of the air-to-air force necessary to gain air superiority over the battlefield. For very practical reasons then, all modern air forces have turned to multirole tactical aircraft. These aircraft place great demands on the pilot because of their diverse mission capabilities. The pitfall is that the real air commander may find himself in a similar predicament as the commander in the previous "ideal" case. Unlike the ideal commander, he always has the right mix of aircraft, but he may find himself with the wrong mix of "expert" pilots. Thus, the first tenet of choosing the right weapon system is to make it user friendly so that an operator will be competent in many mission elements.

Software intensive, integrated systems are ideally suited for the cockpit of multirole aircraft. Software designers could literally come up with a routine for every conceivable mission and every possible technique for executing the mission. However, long before the computer storage capability of even today's aircraft has been exhausted, the gray matter in the pilot's head has registered an overload. The trick is to limit these runaway designs to what we see as viable requirements. Military planners must set these limits because it is not in an aerospace contractor's best interest to offer anything less than everything he can develop. The second point then is to limit the scope of the multirole capability to match realistic requirements. An example of where I think we are going awry will illustrate. At present, we are trying to give all of our frontline fighter aircraft first strike survivability against Soviet type defenses. At first glance this might be applauded until we see the cost of such a decision and realize that it assumes we will not follow the reasonable tactic of rolling back enemy defenses with a specialized force prior to committing the bulk of our fighter aircraft. Additionally, such a reliance on over-capable weapon systems fails to consider low intensity conflicts. During such situations, military tacticians will have to weigh the economic feasibility of using and thus risking such high cost, high-tech weapon systems against low cost targets.

One argument concerning aircraft design is long standing and directly bears on the problem of choosing the correct weapon system. One side of the argument contends that the proper aircraft should be a basic multirole airframe with an integrated avionics suite capable of accepting a large range of strap-on sensors and systems. Their rationale is that this is the least expensive route and allows for a more rapid change of force structure to meet a given threat. On the other hand those who favor fully imbedded systems are quick to point out that strap-on systems tend to have a significant impact on aerodynamic efficiency. Additionally, because strap-on systems are for use on several different aircraft, they are, at best, a compromise on each aircraft. Neither camp is totally correct in my view because strap-on systems have definite limits which may fall short of the threat and totally imbedded systems (all aircraft equally capable) would cost too much. The proper solution is a mix of the two--strap-on systems like the Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) system for the bulk of the fleet; imbedded systems like the EF-111 for specialized mission aircraft.

Any discussion of the right weapon system would be incomplete if it did not consider an alternative to manned fighter aircraft. After the Space Shuttle Challenger disaster, many people questioned whether NASA astronauts were unnecessarily risking their lives doing tasks such as inserting satellites into orbit which could have been done much easier and with no risk to human life using unmanned launch vehicles. In like manner, military planners need to consider the use of unmanned vehicles when the workload gets so high that the pilot becomes a passenger, merely monitoring automatic systems. Similar to the space program, military planners must decide when the cost of putting a human being at risk exceeds the payoff.

Focus on the Operator

With the strength of modern structures and the speed and capacity of state-of-the-art computers, there is little doubt that the limiting factor in todays tactical aircraft is the pilot. Most frontline fighters presently can sustain higher g's for a longer period than the man who commands the machine. Likewise integrated software intensive cockpits already display more information than any one man can

interpret and use. *The price we pay for overloading the pilot's g capability has* been demonstrated all too often with a g-induced loss of consciousness accident. Overloading the pilot with too much information in difficult to understand formats has led to similar incidents due to the pilot becoming disoriented and thus losing situational awareness. The task is to provide a comfortable cockpit with user friendly equipment, and built-in, limited flexibility.

Lets first look at the pilot's "office," for cockpit environment is of utmost importance to efficient and optimum pilot performance. One way to improve the cockpit environment is to reduce the amount of physical work and movement needed to operate the aircraft systems. The HOTAS (Hands on Throttle and Stick) switch mechanization has done a great deal to ease the pilot's cockpit workload. The movement toward HOTAS has to be controlled, however, or the throttles and control sticks in the next generation aircraft will be so overloaded with multi-functional switches and buttons that no pilot will be able to remember all the possible selections.

As cockpit mechanization has improved over the years, one area has not received its fair share of attention--cockpit noise. Noise fatigue is a real phenomenon which can adversely affect pilot performance. In two place aircraft, the problem is compounded by intercom systems which are frequently incapable of filtering unwanted noise. The increased computer power in future aircraft will exacerbate this problem even more since increased computer power seems to go hand in hand with larger demands for cooling air--a primary source of cockpit noise. New active noise reduction systems are undergoing tests now which hopefully will alleviate this often overlooked problem.

Equipment designed with the pilot in mind must be user friendly in more ways than the words imply for desk top personal computers. It is true that this type of user friendliness is necessary, but the harsh cockpit environment requires consideration of display size, format and controls along with switch and button design. Displays must be large enough and clear enough that the pilot can quickly focus on them. A display whose information can not be registered and interpreted at a glance can be more a hazard than an aid. Aircraft control suffers during any use of such a display. However, size is only part of the equation. Information must be displayed in a format which does not require study to decipher its value. If too much information is presented on a given display, the pilot will have to literally read the display looking for the needed information, regardless of display size. When flying at 100 feet at night, reading a 'book" can be deadly. Finally display brightness must be easy to adjust with nominal default settings for day and night. There must not only be a balance among displays, but different formats on a given display must also be balanced. This is especially true when changing the input to a display from a video input like radar or infrared to a text display or vice versa. Display brightness and contrast should only have to be adjusted once in a given lighting situation.

Workload in the cockpit can be tripled simply by selecting the wrong type of controls the pilot must use to control his software intensive cockpit. Touch sensitive screens are efficient and well suited for the laboratory or simulator environment, but their suitability for operation in the cockpit of an aircraft flying at 100 feet at night is in question. If you add the effects of turbulence which is frequently found when operating at low altitude, the problems associated with such controls become more than an occasional switch error. They drive the cockpit workload up to a point that aircraft control is sacrificed for something as simple as a mode change of the radar system. The pilot finds himself fixing his entire *attention on trying to place his finger in* a specific place and *touching that* place *only once*. Again, at 100 feet at night such fixations can be fatal. The solution is to use controls which give tactile feedback when operated. Keyboards should be designed with handbraces to allow operation in turbulence and, in some cases, should allow for "blind" usage through the use of various shapes and surfaces.

As mentioned in the previous section, the software intensive cockpit is ideally suited to the multirole aircraft. The versatility which high speed digital computers brings to the cockpit of even the smallest fighter aircraft is impressive. It allows for a degree of flexibility which is hard to comprehend. Literally any cockpit set up or mission profile can be programmed allowing satisfaction of every whim of every pilot. This flexibility, however, breeds complexity which at best presents a tremendous training challenge and at worst breeds confusion which may be fatal in a low altitude tactical situation. One example of this can be found on the early prototype, LANTIRN-compatible F-16 aircraft, the original version of the Multi-national Staged Improvement Program (MSIP). The flexibility which was built in to the design allowed the pilot to have nearly any combination of displays and system submodes available to the pilot through his own tailored master modes. The problem was that since the system remembered the last pilot's selections for master modes, each pilot had to program each possible master mode or risk being surprised in the air by a combination he did not recognize and could not use. The ultimate problem of this flexibility was evident when the LANTIRN system was installed. In this case, a pilot who had failed to properly program his master modes could easily lose his terrain following guidance due to an accidental switch activation. The loss of this guidance while flying at night in the mountains at 200 feet will cause the heart of even the most stalwart pilot to miss a beat. Such an experience is a rapid cure for proponents of rampant flexibility. My experience in operational fighter squadrons is that only a small percentage of the pilots ever use *the flexibility sewn into the modern cockpit. The average fighter* pilot does not want to have to choose every display combination and format for each mode of operation. Thus, as important as it is to have the right amount of flexibility built into the software intensive cockpit, it is even more important that well thought out default formats be available for each mode, formats which will automatically be displayed upon initial power-up if the pilot has taken no action to change them. Additionally, there must be an easy way to get back to these default modes if in the heat of battle the confusion factor becomes so high that the pilot wants to get back to basics quickly. In sum, make the flexible cockpit a pilot option not a mandatory planning task.

Finally, keeping the pilot in mind during cockpit design means unloading cockpit duties to the planning room. The beauty of the software intensive cockpit is that with a simple interface all flight planning, whether it's navigation planning, threat planning, or delivery planning, can be completed away from the cockpit and loaded into a small cassette for transfer to the aircraft computers. Planning and data entry can be completed in the quietness and comfort of an office environment with all available technical data within easy reach. Entries can be quickly checked and double checked to eliminate keyboard

errors which could easily turn a successful mission into a confusing failure when hastily typed target coordinates later proved to be in error. Such data transfer units are in use now and their use should be expanded. Threat data from the intelligence branch should be included so that the latest information on enemy defenses is displayed on the digital map presentation. Moving data entry from the cockpit to the planning room allows the pilot to concentrate on his primary task of flying the mission.

In summary, designing for success in the next generation of tactical fighters must start by choosing the right systems and then remembering the limitations of the human operator.

MAYBE SOMEDAY

Mission planning continues to be the key to mission success. With proper system design, we can minimize the workload of both the pilot in the aircraft and the pilot in the planning room. We can even transfer some of the pilots preflight planning to "others," but mission planning will always be with us in some form.

Perhaps someday as the mission commander briefs his pilots on the details of their mission prior to stepping to their aircraft, his words will be "heard" by a voice activated computer which will change his briefing into individual fully planned profiles for each pilot. The computer, which is constantly updated with weather, intelligence and tactics information, plans the profiles based on its near perfect knowledge of weapon and system capabilities. Attack routes are chosen to bypass defenses or to defeat them if the capability exists within the mission aircraft. Since the computer does all the planning for this strike force and interfaces with all other mission planning computers, conflicts in attack routes are eliminated. After the commander completes his briefing, each pilot picks up his cassette containing all the data needed to complete the mission.

Once airborne, the pilot is presented with a briefing approaching each turnpoint by the aircraft central computer through voice and graphics describing the charcteristics and any dangers associated with the turnpoint. Approaching the target area a similar refresher from the mission briefing is given along with any updated information about threats received through on board sensors or down-linked from airborne surveillance platforms.

Throughout the mission, the pilot is constantly fed information to help him fly the mission safely and successfully. This information is presented to him in the easiest to interpret formats for human beings: voice and pictures. Mission success is practically guaranteed. Sound like Star Wars? Yes.

Well maybe someday--but not today.

HUMAN LIMITATIONS IN FLIGHT AND SOME POSSIBLE REMEDIES

BY

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SUMMARY

The biodynamic effects of high speed flight can produce sudden loss of consciousness without warning whereas most aircrew are used to the prodromal loss of vision. New advances in anti G systems design can improve G tolerance but training is foreseen as the short term answer to this problem. Later aircraft will use pressure breathing and improved garments as these alone offer substantial gains in G tolerance.

Amongst the environmental stresses that limit performance are thermal, vibration, noise and NBC defence. Personal conditioning is of benefit under high thermal stress, active noise reduction can limit the reduction of noise at the ear and NBC defensive ensembles protect against NBC agents. Much remains to be achieved in the field of vibration attenuation.

The design of the man machine interface can both enhance and detract from crew performance in flight. Head up displays, night vision goggles, helmet mounted displays, computer graphics, digital maps and integrated sensor displays can be viewed as new features which greatly increase mission capability. The requirements for audio recognition of electronic threats and the use of colour are areas which can, if used unwisely, mitigate against crew efficiency.

Finally, cockpit and system automation offers the chance of significant advances in cockpit design as management tasks can be completely relegated to the electronic crew member, leaving the human as the ultimate decision maker involved only when absolutely necessary.

INTRODUCTION

There can be little doubt that man will continue to crew combat aircraft well into the future. Remote piloted vehicles have been with us for some time but their utility can be measured in terms of their limited growth in numbers. Battlefield surveillance in VMC is perhaps one area where they have much to offer. In all other conditions, the inclusion of the human computer is seen as the most cost effective payload in combat aircraft despite the limitations of the crew in advanced combat and high threat environments.

This paper will examine some of the human limitations in flight and some possible remedies as a guide to designers who have a significant role in the sophistication of the man machine interface.

BIODYNAMICS

The principal hazard for limitation of performance is the haemodynamic effect of the sudden or rapid application of acceleration forces on the crew consequent upon rapid manoevres which change flight path vectors. The belief that the more manoeuverable the aircraft the less vulnerable it is to hostile action has bred a new generation of high performance aircraft which have large thrust weight ratios and high manoeuverability. In fact, some of the newer aircraft are designed to be inherently unstable in flight so that the response to the manoeuvre is enhanced. These aircraft require computer control to guarantee stable flight at all times.

The cardiovascular demands of high sustained acceleration (G) forces limit human performance because when the perfusion of the eye and brain fails, sight and consciousness are lost. This problem has been realised since the 1920s and many protective measures are now incorporated in aircraft systems. However, within the last few years an added hazard had found prominence which concerns the rate of application of the acceleration rather than the level of acceleration itself. Figure 1 shows human tolerance to applied positive vertical acceleration (+Gz) with respect to time. The more gradual rate of application (line x) shows that there is a warning area (cross hatched) where sight is impaired before the loss of consciousness (G - LOC). This is because although the eye and brain are at a similar level above the heart, the intra-global pressure of the eye causes orbital blood perfusion to fail before that of the brain. Thus the pilot knows that when his vision dims or colour perception is impaired, loss of consciousness

is not far behind. However, when the rate of application of G is high (line y), the warning zone of loss of vision (grey out) is absent and the pilot looses consciousness without any warning. This loss of consciousness has a mean time course of 15 seconds because although the manoeuvre demand from the pilot ceases when he loses consciousness, it still takes some time for the aircraft to change its flight path and for the blood pressure to recover sufficiently to restart perfusion in the brain. At any flight level this loss of consciousness is unacceptable. At low level it is fatal.

Both the USAF and the RAF have surveyed their aircrew to determine the frequency of these occurrences. Both the USAF (Pluta, 1984) and the USN (Johanson and Terry, 1986) found that 12-14% had experienced one or more episodes of unconsciousness in flight and in one high performance aircraft, the F-16, the incidence rose to 30%. Prior (1987) found in the RAF that 19% reported at least one episode of G-LOC and that the majority occurred in jet aircraft of modest performance (trainers) where no anti G system was provided. He also reported prolonged recovery times in many incidents with a variety of symptoms reported. The USAF have attributed several fatal aircraft accidents due to G-LOC and all western Air Forces are actively pursuing methods of enhancing G protection. The USAF and other NATO Air Forces use centrifuge training as the experience of G-LOC under controlled conditions plays a vital role in its later avoidance. The centrifuge experiences enable aircrew to watch their performance on video, to refine their anti G straining manoevres (AGSM) which can be further developed in flight.

Some new developments to counter the hazards of G-LOC are as follows:

It has been shown that the higher inflation pressure schedules (eg p=1.25 Gn - 1) do provide enhanced G protection but when severe discomfort is produced, systemic blood pressure and hence G tolerance is reduced. The USAF ready pressure valve which pre-inflates the suit to 0.5psi produces improved G tolerance as the time to full inflation is reduced. Gas flow times can be further reduced by electronic servo valves which have the great advantage of being easily programmable as manoevre demands change. However, these valves have yet to show improved G tolerances. The pulsatile types of valve ("bang-bang" Albery et al, 1987) have demonstrated improved G tolerance but only as far as the mean pressure is increased relative to steady state values. Perhaps the non-linear valves (Cammerota,1987) now under development may show improvements in G tolerance which have evaded other designs. Although it might be considered that early or even pre-inflation of the anti G suit might enhance G tolerance, experiments have failed to demonstrate any improvement with these schemes.

The suit which applies counter pressure to the abdomen and lower limbs has seen few radical changes of late. The suit works by increasing peripheral vascular resistance in the areas covered which, in turn, elevates the systemic arterial pressure to permit perfusion of the head under applied positive vertical acceleration. Basically, the garment comprises an inflatable bag supplied with gas under the control of anti G valve with the bladder tailored for comfort and movement. The internal anti G suit worn next to the skin and undergarments works best as there are fewer compressible layers between the suit and the arterial tree. However, this makes for difficulty in doffing the garment between flights hence the development of an external garment. This is worn over the coverall and corporates the pocketry and other external features of that garment. There are small but demonstrable differences between the protection of the internal and external suits but most aircrew have made the choice of the external suit on comfort and ease of use. Extending the coverage of a garment may improve the protection somewhat but at the risk of worsened comfort. In particular, the extension of coverage to the buttocks may well reduce comfort under the lap restraint straps as the pelvis is elevated by the expanded buttock bladder.

One of the more significant improvements in G tolerance has come from an increase in breathing or intrathoracic pressure when G forces increase. The anti G straining manoevres that pilots are taught increase the intrathoracic pressure which increases the arterial pressure as a whole. However, this can be fatiguing. The pressure breathing valves that are necessary to maintain tissue oxygenation at altitudes above 40,000 ft can be adapted to become acceleration sensitive so that they increase breathing pressure when G is applied. Recent experiments using these techniques have shown not only a considerable reduction in fatigue but also a considerable enhancement

of G tolerance. The changes in the chest wall size can be minimised by counter pressure garments such that gas is applied not only to the anti G suit but also to a similar garment worn over the chest. The pressure gradients between anti G suit, pressure breathing and the chest counter pressure garments can be varied to select the optimal G tolerance. Speech difficulties can be minimised with training under such regimes and the enhanced G tolerance more than compensates for these disadvantages.

As perfusion in the head under +Gz is an inverse function of the distance of the head above the heart, reduction of the head to heart distance by reclining the aircrew seat rearwards or even forwards (prone) will enhance G tolerance. Rearwards reclination provides a more comfortable position as a sitting position is achieved with all body weight including the head being supported by the seat. A prone lying position can reduce the head to heart distance to zero but at considerable ergonomic disadvantages in the positioning of controls and displays and the much reduced fields of external vision. The reclined sitting position also restricts rearward vision somewhat as a high degree of tilt is necessary to provide significant G tolerance improvement.Furthermore, both prone and reclined positions introduce new problems of assisted escape in the security of the ejection path and successful escape path clearance. It is for these reasons that few aircraft either in service or projected use extensive reclination or prone positions as ways of enhancing G tolerance.

The problem of G-LOC at low altitudes and the need for adequate ground clearance at all times has prompted some authorities (Lewis, 1987) to advocate the use of the electro-encephalograph (EEG) as the detector of G-LOC. During unconsciousness, the EEG changes and slower rhythms appear. It is proposed that a detector circuit would seek these rhythms and then take over control under G-LOC to provide an upward flight path vector until consciousness was regained. It remains to be seen whether the reaction times of this device together with the disadvantage of scalp electrodes makes this a viable strategy for improved flight safety.

ENVIRONMENTAL

The environmental hazards that present and future aircrews will be exposed to are legion. None are particularly new but the severity and combination of the types of hazard increase markedly as aircraft performance increases. High speed low level flight is often accompanied by thermal stress as the sources of heat from solar glare, cockpit avionics, crew metabolism combine with that of aerodynamic heating to make efficient cockpit conditioning essential. However, such is the complexity and insulation of aircrew clothing needed to combat hypothermia following cold weather immersion after ejection that personal conditioning rather than cockpit conditioning is required. Personal conditioning can be effected by passing a cooling medium, either air or liquid, by means of a special garment over the skin to extract heat when required. These systems are particularly useful when cockpit conditioning is inefficient for example on standby on the ground, taxying or in very hot climates. The same system can be used to warm the crew under cold conditions. Vapour pressure refrigeration or thermoelectric devices can be used as heat sinks or heat sources.

Thus the combination of cockpit and personal conditioning offers the possibility of ensuring thermal equilibrium of the crew under all conditions of flight and, with separate portable supply systems, even after emergency escape. Unfortunately it has proved difficult to add these systems late in aircraft development despite their comparative simplicity. Newer efforts are required to define more accurately the predicted thermal loading in flight in new aircraft and instal systems early while engineering options are flexible.

High speed low level flight introduces severe vibration spectra as the more complex aerodynamics permit faster flight closer to the earth surface where detection by enemy forces is more difficult. Higher wing loading usually permits the avoidance of many of the more damaging and high amplitude vibrations but in turbulent and gusty conditions the vibration imposed upon the aircrew makes external and internal cockpit vision difficult and induces spurious movements to the body and hands which increases control difficulties. Although the criteria for permissible vibration in flight have been accepted for some time, high performance aircraft and their crews are subjected to the hazards of vibration and there seems little that can attenuate it. In helicopters, vibration attenuating seats have been used (eg Westland Lynx) but the attenuation in axes other than the vertical were less than ideal and much remains to be done. Vibration attenuation in ejection seats has rarely if ever been attempted.

Noise in aircraft is generated by power plants, gear boxes, propellers or rotors, aerodynamics, avionics and armaments. Few aircraft exhibit all these types but high speed low level flight in fighter aircraft have the critical combination of severe aerodynamic and engine noise coupled with particular noise patterns generated by engine intakes and canopy designs. The impulsive noise from guns or missiles is intensive but usually brief. Against this severe noise background aircrew are required to listen and communicate with a multiplicity of ground and air stations, to interpret audio signals from missiles and radars, both hostile and friendly, and to listen for and act upon audio warnings of varying degrees of urgency both verbal and non verbal,- in all a severe conflict of requirements. Noise exclusion can be provided by improved types of helmet and ear telephones and filtering devices can be incorporated to permit only the essential audio spectra to be heard. Active noise reduction can be produced by measuring the unwanted noise at the ear by a small microphone, inverting it electronically and reinserting it in the signal to the ears so that the noise and its inversion will cancel each other, so leaving the incoming signal unimpaired. Laboratory and flight tests have shown that this system to be feasible and it will be incorporated in many new aircraft. Better aerodynamic design may also reduce noise in flight but the requirement for more powerful engines and complicated electronics are likely to negate any noise reduction from improved intake and cockpit canopy designs.

The tactical advantages to an enemy of nuclear, bacteriological and chemical (NBC) weapons is undeniable. However, providing aircraft and aircrews can be protected from these hazards and allowed to complete their missions, the advantages of these weapons to an enemy is severely reduced. Of the three, the chemical is judged to provide the greatest threat to aircrew because of its speed in action and the varied methods of deployment. Much effort has been expended by all NATO forces in the research and development of methods to protect aircrew from chemical toxic agents.

All methods rely on absorption of the agents by suitable filters and impenetrable clothing to prevent the agents reaching the skin, conjunctivae or respiratory passages. That adequate protection can be provided there is no doubt but the physiological load that such protection imposes is considerable. Reduced immobility, reduced fields of vision, slower and more complex donning and doffing procedures and heat load are amongst the more serious effects of using NBC defensive ensembles. Rest, relaxation, ablution and feeding all become much more difficult when wearing NBC apparel. The reduced efficiency in flight caused by NBC clothing is difficult to quantify but has often been reported.

Exercises have proved that aircrew can complete their mission successfully with effective sortie generation and repetition. In these exercises the complaints of aircrew about the ensembles usually revolve around minor irritations that subsequent modifications have removed to a large extent. However, the heat load remains in hot climates and the application of personal conditioning by closed loop liquid systems would do much to answer the complaints here. Experiments have shown that the NBC ensembles and their associated drills become more acceptable the more they are worn and performed. Experience should improve the confidence of aircrew and minimise the reported reduction of efficiency in flight.

COCKPIT INTERFACE

The role of the aircrew in modern high speed combat aircraft is becoming more of a manager of systems than pilots, navigators or weapon operators in the conventional sense. Modern aircraft have computers that can fly the aircraft, navigate over the whole sortie, detect and acquire targets and fire weapons completely automatically if required. However, if it were as simple as that there would be no need for aircrew. In truth, the most space efficient computers of all are the aircrew themselves.

Although much of the management process can be delegated to automatic systems, there is still too much for the aircrew to do. One of the current problems is situational awareness where the aircrew need to know enough to hold a true model of reality of the outside world to ensure the efficiency of the flight. On occasions they may become overloaded and thus cannot prioritize the inflow of data so that important messages are lost and awareness of the true situation suffers. It is not only what data are required but when and in what form. Vital information which requires an immediate response to avoid disaster must take precedence over all but there are many other information sources of lesser importance which, if neglected, could lead to loss of control, loss of a way point or misidentification of a target. The mass of data that must be made available to the aircrew has led to the information implosion in the cockpit. As an example of the multiplicity of data streams and associated controls of a current high performance aircraft, the F/A 18 Hornet cathode ray tubes display

675 acronyms, 177 symbols, 73 threat and danger warnings, 40 multifunction display formats and 22 headup display configurations. In addition, there are 200 film strips and maps on the horizontal situation indicator, 59 indicator lights, 6 auditory warning tones, 19 push buttons on the up-front panel, 9 switches, mostly multifunction, on the throttle and 7 switches on the stick (Taylor, 1986).

The Head Up Display (HUD) was developed as a means of permitting the pilot to see the outside world while still viewing the instrument display. Of its utility, there can be no doubt, however, the increase in the amount of data that can be displayed on it leads to considerable cluttering such that many modern HUDs have a "declutter" mode where only essential data are presented. That this particular feature is necessary is seen by the occasions, in simulators, where attention to the HUD detail has diverted attention from the landing runway seen through it such that attempts have been made to land on obstructed runways (Fisher et al, 1980).

Computerised recognition of radar emissions and electronic counter measures will play a significant role in any future combat. This is because many of the weapons acquire targets by radar. The various types of weapon have differing electronic signatures and evasion from the weapon will require recognition of the type of weapon and thus its capability. Moreover, one will need to know whether that weapon is in flight and how far away. This recognition will be computer assisted but recognition of an audio analogue of the radar may well be the responsibility of the crew. As many of the weapons that are likely to be deployed in war may be unknown to the opposing forces, recognition is likely to be an all or nothing case. Furthermore, the computer memory may well be deficient if new types of weapon appear. Thus the audio channel will grow in importance as a data source and high audio workloads may well impair audio discrimination. Whilst electronic counter measures may well be deployed automatically on the receipt of certain signals, manual control is likely to be required over missiles and their signals as crews will be reluctant to devolve this control which will have such a marked effect upon the success of the sortie.

Visual enhancement devices or night vision goggles (NVG) magnify the ambient light to levels that permit operations at night solely by visual reference to the outside world. These devices have reached a level of sophistication that permits sorties to be flown almost regardless of light level or weather conditions. The devices increase capability and operational flexibility considerably but increase the workload on the crew as the devices are limited in instanteous field of view, they lack depth appreciation or stereopsis and have as yet no colour discrimination. Thus other clues are need for successful mission completion or terrain avoidance. More frequent head movements and cross checking with instrumentation or maps are activities which improve confidence but the limited field of view at high turn rates can limit operations in hilly terrain. In order to prevent NVG saturation, all cockpit lighting can be screened at 600nm so that a blue green colour reflection of the instruments is seen by the naked eye below the goggle but the reflected light is too short in wavelength to be amplified by the goggle itself.

An extension of the technology of visual enhancement devices is to display flight and other data on the aircrew helmet itself utilising the reflective properties of the protective visor. This means that unlike that the HUD which only projects information when looking along or near the aircraft bore-sight axis, whatever the direction of the head is pointing data are displayed into the eyes of the crew. These displays can be used both for giving information to the crew and to the aircraft system itself. In the former case, warning, engine or flight data can be collimated at infinity and occluded if necessary at extreme head angles.In the latter case,the display can act as a weapon sighting device. For this the head and eye axis is measured accurately by a cockpit sensor system and the head position is used to direct missiles or guns. The operational advantages of the device tend to overload the visual channel of the crew with the added problem that any differential movement of head and helmet caused by vibration reduces the accuracy of the system. Moreover, displays on helmets usually mean more complex and heavier helmets which have to be borne by the crewman magnified many times under acceleration. No one has yet proposed a counter balanced system whereby the helmet weight is carried by the aircraft or seat. Although this is an obvious solution, the problems of ensuring freedom for all degrees of head and neck movements during flight and the precise separation on emergency escape are difficult to overcome.

We are all aware of the importance that colour plays in visual discrimination. Because it can now be easily simulated in electronic displays, there is a tendency to provide colour in symbolic displays as an aid to discrimination. Unfortunately, the colour coding is unnatural and is not intuitive. Furthermore, there is already an international agreement about the use of three to five colours for cautionary and emergency warnings. These colours should be avoided otherwise confusion arises. The skilful use of colour in all types of displays should reduce workload but unless the coding is simple

to understand and unambiguous, it becomes another variable in the visual channel which is already well overloaded. Colours can be used to group data and when no search is required, tasks can be simplified by colour. Hue is useful to signify qualitative differences whilst tone can present quantitative data but care must be used less the hue and tone differences become eroded with changes in cockpit illumination.

The ability of wave form and signal generators to create a wide variety of presentations in shape, size and boundaries can be used to present simulations of the outside world when the external view is denied or discrimination too poor to be reliable. Fixed symbols are already widely used but the ability for the electronic symbol to change shape, size, colour and position as data dictate presents an almost limitless array of display formats. No wonder that modern aircraft cockpit resembles the video arcade and computer games already in widespread use. Guidance principles for computer graphics recommend (Easterby, 1970) that symbols should present a strong boundary with high contrast against their background, the form or shape should be simple in outline rather than detailed, the shape should be stable and unambiguous and symmetry is an advantage in recognition. Where symbols are grouped or classified they can be enclosed in open structures for ease of recognition. Other approaches are to display pictures in action such as branching diagrams which can be used for various menu selections or sequential actions as in check lists with the correct procedure highlighted or accentuated. In this manner the eye is guided through the detail, the correct action paging sequential displays. These concepts follow the logical thinking process and lead the pilot through the displays rather than requiring him to drive it. "Help" sequences in computer systems have a similar function.

One item of cockpit equipment that can be more simply and accurately replaced by computer software is in the realm of cartography. The ability to store limitless areas of maps, over many scales, with relief contouring or colour coding, bearing tactical notations,updates or alphanumeric overprints has enormous advantages over the older methods of pre-prepared hand held maps. Land form recognition is essential for navigation, terrain avoidance and survival in hostilities and the digital presentation of the land mass under the aircraft moved by the inertial navigator in accordance with the aircraft flight path promotes a dramatic improvement in operational capability. Topographical data are static but tactical situations are dynamic and require constant refreshing. This can be effected either pre-flight or in-flight as new targets are located. They can be marked and stored in the digital database for post-flight debrief. Track ball or skew controls can be used to move symbols and co-ordinates as pen controls or to interrogate the display for height data. Scroll selections can be made to look well ahead or laterally or to search for other features at some distance from the present position. North or track orientation is selectable with the alphanumerics and overlays always appearing the right way up. Finally, illumination can be made automatically compatible with all ambient levels and with all types of visual enhancement device. Digital maps can thus be seen as a major advance in cockpit design that diminishes the limitations of the human operator.

The use of forward looking sensors can provide vision at night, in cloud and in poor visibility. This is especially useful when the aircraft must remain passive and no radar emission is permitted. Under these conditions forward Looking Infra Red (FLIR) systems combined with NVG can be used as each complements the other. FLIR data when presented head up in raster form and then visualised in turn by a NVG produces a greatly enhanced view of the outside world by data matching. FLIR detects the thermal image of the ground in monochrome but is obstructed by heavy precipitation, cloud or fog. However, particle size is important and FLIR is often available when normal vision is completely obstructed. Any temperature or absorption difference is shown in FLIR, cold areas where shadows have been can show the previous locations of parked aircraft, colder patches on aircraft wings can reveal newly filled fuel tanks. NVG in contrast only use reflected ambient light and highly illuminated areas appear as bright spots on the display. The NVG mounted on the head represents all round vision with head movement whilst the FLIR data is concentrated in the narrow head up display. The integration of these two separate sensor devices produces the capability to operate in conditions never possible before.

The visual channel is well utilised in all modern aircraft and over used in many. As workloads have increased, the voice channel has been developed both as means of receiving data and also a means of control. Audio systems are by no means new features in aircraft. Bells, buzzers, warnings and chimes are all in regular use and analogue tone changes have been used as speed warnings on Naval aircraft where it proved difficult to display analogue air speed data head up. New systems use both verbal and non verbal warnings and the spoken "pull-up" demands in ground proximity warning systems have already established their worth. However, the newer applications are in the areas of verbal control of aircraft systems where no other control channels remain available. Experiments have shown that with even fairly ineffective microphones in noisy masks, systems can

recognise accurately up to 92% of a 50 word vocabulary using unskilled operators (Poston,1986). Moreover, when comparing voice data entry to that by keyboard, responses to cues for data entry were faster by voice. Errors were made more frequently with voice but this was due to the greater number of data bits required by voice than by keyboard but subjective preference was overwhelmingly for the voice channel. Furthermore, this experiment permitted easy keyboard use. Where there is no possibility of fast keyboard entry, voice entry comes into its own even under conditions of severe vibration.

To offload the aircrew during a difficult and complex mission,a system is required to manage all those aspects of the mission which do not require the crews' direct intervention. Most systems have built in automation where microprocessor control regulates much of the technology already and the crew are only warned where urgent rectification is required. However, it can be argued that if the crew can rectify the problem so could the system thus bypassing the crew. Only when operational capability is seriously threatened should the crew be involved. Now that philosophy can be extended to other areas of the aircraft, particularly the weapon system. The aim is to produce a pilots' automatic assistant, a software package to aid the pilots through attack mission by managing displays, tasks and performing much of the attack itself. One system under development for the US Navy (McElroy,1986) uses a radar module which recognises radar profiles by reference to a built in library and highlights the recognition and classification features of the individual profile. Filtration and averaging techniques over many images further refines the data and a smooth profile is identified and presented for pilot acceptance. Another module uses video data to track and counter hostile surface to air missiles (SAMs). The system analyses the radar signal and selects the appropriate counter measure. It tracks the SAM, confirms its type and capability and, when opportune, requests the pilot to authorise the counter measures. A third module manages the crew interface. It senses and analyses all data either arriving, leaving or generated within the aircraft. It tracks the aircraft position and the positions of all other aircraft and ships, hostile or friendly. It examines probable and possible moves and counter moves of other aircraft and ships and presents solutions to the pilot updating his situational awareness. It prioritizes the threats and automatically moves on to other tasks. Only when the system demands an authorisation from the crew are they addressed. Thus the crew become aware of the situation only when they need to and in time so they can react to it. Only when the system fails is manual control again required. Further refinements to this concept surround the ability of the systen to learn as it acts, fine tuning the decisions it takes, requiring less and less intervention from the crew. It is expected that much will be achieved in this important area as it offers the greatest relief to the crew in the mission enabling then to maintain maximal visual search and aircraft control at extreme speeds low level, the only flight regime in hostile areas where survival is likely.

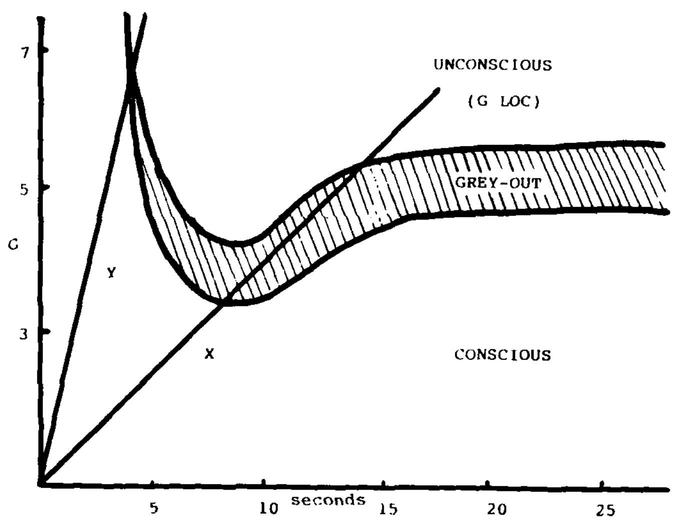

FIG 1 G-TOLERANCE AND TIME

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THE PILOT IS NOT THE LIMITING FACTOR IN HIGH PERFORMANCE AIRCRAFT

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SUMMARY

The physiologic requirements to validate a $+G_z$ tolerance model based on arterial pressure (Pa), eye-heart vertical distance (h), and hydrostatic pressures (P_H) are investigated. Venous return (VR) and intrathoracic pressures (P_I) are considered the major physiologic parameters involved in supporting this model at levels above 9 G.

Venous return was determined to be adequate to support Pa during either relaxed lower-level G tolerance or high sustained G. Some concern exists regarding VR during long duration G exposures, because of the delayed compliant nature of veins.

P_I, the physiologic basis for the anti-G straining maneuver (AGSM), was found to be a function of inspiratory volume (V_I); and, therefore, as the subject is reclined ($+G_x$) to reduce h, the reduction in V_I prevents a maximum AGSM limiting tolerance to 15 G. On the other hand, pilot pronation ($-G_x$) may not limit V_I, and higher G tolerance may be possible. Neither physiologic function, P_I or VR, appears to limit G tolerances up to 15 G.

Fatigue was recognized as an important dimension of G tolerance and, as such, was examined as a limiting physiologic function at high sustained G. Primarily, because of the functional coupling between G-level and G-duration tolerances, if one is not G-tolerance limiting, neither is the other.

INTRODUCTION

Recently, we developed a model for predicting pilot G tolerances that considered all proven methods for increasing G tolerance (1). This model included various seat back angles, as large as 75° (from the vertical), that are considered practical for piloting aircraft. Although this model was developed to interrelate various methods of G protection so that a mean G tolerance could be calculated up to 9 G, G tolerances of 20 G are predicted--a level that far exceeds the 9 G of today's fighter aircraft (Fig. 1). Yet, today, we frequently hear that the pilot is the limiting factor in maneuverability (the development of G forces) in today's high performance aircraft.

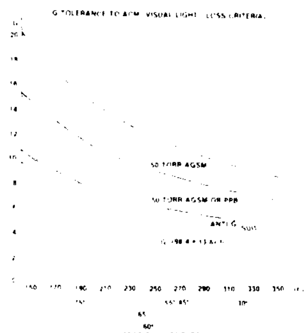

Figure 1. G tolerances are shown using known methods of G protection for a group of pilots (1).

The pilot has always, to some extent, been considered the limiting factor. G-induced loss of consciousness (G-LOC) frequently occurred in pilots flying "high performance" aircraft in World War I (WWI). Snoopy and the Red Baron were the limiting factors in such advanced aircraft as the Sopwith Camel and Triplane, and the De Havilland 4 (2). Yet, today's pilot easily tolerates higher G levels than those that occurred in WWI, not because the pilot's G tolerance evolved with advances in fighter aircraft technology, but because of the evolution of the pilot's life support equipment. Therefore, when we state that today's aircraft and those on the drawing boards are "pilot limited," we really mean that these aircraft are "anti-G equipment limited." This assumption, however, is valid today if we are only aware of life support equipment that has been developed, tested, and is ready for operations. If suitable equipment is potentially available and as effective as the model suggests, why, then, is the pilot considered the limiting factor?

This seemingly paradoxical situation requires that three questions be answered--the last of which will be the topic for this article: (a) Is the pilot necessary in future fighter aircraft, or has the time for pilotless (robotics) aircraft arrived? (b) If adequate anti-G methods are known and available, why are they not operational? (c) Is our model really G-tolerance predictive above 9 G?

The first two questions have been considered recently, in Aviation, Space, and Environmental Medicine, in a Guest Editorial entitled, "A Perspective on Human Performance As the Limiting Factor in Aircraft Performance" (3). In this article, the author concluded: (a) that the pilot was not the "limiting factor," but the "enabling factor" in current and future fighter aircraft, thus clearly relegating the robot to a role in the more distant future; and (b) that, in regard to G protection which is available but not operational--the limiting human is not the pilot in the air, but "can be found in a number of places on the ground."

The final question, therefore, invokes the validity of our model in predicting G tolerances above 9 G for pilots using various anti-G methods, in combination or separately. Using known technologies, this model predicts that pilots could conceivably tolerate 20 G. Of course, as data are extrapolated in the development of predictive models, variables that cannot be necessarily identified nor predicted may cause these "far reaching" extrapolations to become meaningless.

That the human can function at a 20-G level is not inconceivable. Humans have been exposed to +15 G_x without serious physiologic consequences. The limiting factor was apparently the inability of the subject to breathe, because of the work required to expand the lung against the applied $+G_x$ forces (4-6).

But, if an individual is not completely reclined (thereby possibly reducing the consequences of this problem), and if he uses such available anti-G methods as assisted positive pressure breathing (PPB), what are the physiologic limitations that can now be accurately predicted? If none exist, as determined by use of the physiologic data we now possess, then maybe a pilot using assisted PPB can tolerate 20 G in a 75° reclined or pronated seat. In this article, therefore, we shall explore possible limitations; and we shall consider some physiologic functions that must prevail if this model is to have any significant predictive value. To this end, we will examine the physiologic bases that make this model predictive, using appropriate research that supports the validity of this model's predictability.

In addition, we shall consider the other dimension of G tolerance: fatigue. Over the last decade, this measure of G tolerance has grown in significance until it is now considered as important in pilot protection as G-level tolerance.

PHYSIOLOGIC BASIS OF THE MODEL

The development of this model was completely mathematical, based on simple hydrostatic pressure principles. If this model is to be predictive for high G tolerances, however, some basic physiologic concepts must be considered.

Venous Return:

A major physiologic premise regarding this model, as it predicts "relaxed" G-tolerances, is that adequate venous return is available to support the arterial pressure at head level during increased $+G_z$. Our model is based on Pa, generated by the heart, that is opposed by hydrostatic pressures that develop within the body during exposures to $+G_z$ forces. These hydrostatic pressures, caused by an increase in G, can be calculated:

$$P_H = hdg \quad (1)$$

where:

P_H = hydrostatic pressure in mmHg

h = height of a fluid column

d = specific density of the fluid relative to that of Hg

g = ambient accelerative inertial force (G)

Using Eq.(1) with a column height of 330 mm (eye-heart vertical distance in an average erect human), and a fluid specific density for blood relative to Hg (13.6) = 1/13.6, the effect of any G level on P_H at heart level as measured in millimeters of mercury can be calculated. In the erect human body, this pressure is opposed by a mean Pa of approximately 100 mmHg. As P_H increases and Pa-P_H approaches intraocular pressure of 15-20 mmHg at eye level, arterial blood flow to the retina ceases, and G tolerance is established, in which case:

$$Pa = P_H \text{ or } Pa = hdg, \text{ or}$$

$$G = Pa \cdot d/h \quad (2)$$

where:

G = G tolerance (blackout)

Pa = arterial pressure generated by the heart (98.4 mmHg)[1]

d = 13.6

h = 330 mm.

This equation, if predicting relaxed G tolerances in humans, assumes the very important fact that there is sufficient venous return, so that the heart has the required blood volume to maintain adequate cardiac output.

Three studies have measured relaxed rapid onset rate (ROR) $+G_z$ tolerance and the eye-heart vertical distance (7-9). The results of these studies are compared using Eq.(2) and, in Fig. 2, showing the existence of a very close correlation. We can assume, therefore, that venous return is adequate to support cardiac output, and with vasoconstriction (sympathetic responses) maintains Pa at a level that opposes P_H as calculated using Eq.(2).

Eye-level direct Pa has been measured during peripheral light loss (PLL) in humans at the onset of G, both with and without an anti-G suit (10). As expected, and as shown in Fig. 3, Pa decreases with the increase in $+G_z$ to a level at which PLL should occur; but apparently, because of energy reserves in the retina and brain, vision is not lost and some Pa recovery occurs. This latent period, during which light loss and loss of consciousness will not occur, is about 5 s, and has been measured by Beckman et al. (11) and, more recently, in our laboratory. At about 5 s, a rebound in Pa occurs. However, this increase in Pa does not continue. In fact, a decrease follows, resulting in PLL; and the G tolerance is established.

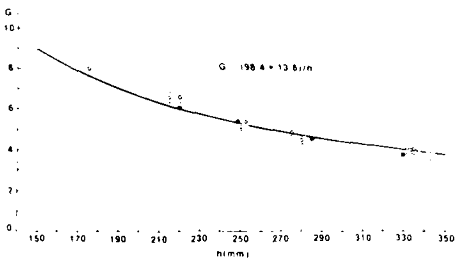

Figure 2. G tolerances of relaxed subjects wearing an uninflated anti-G suit, as determined using Eq.(2) of text. Data represented by: open circles (○), (mean ± S.E.M.) are from Burns and Whinnery (7); open squares (□), from Burns (8); and closed circles (●), from Crossley and Glaister (9).

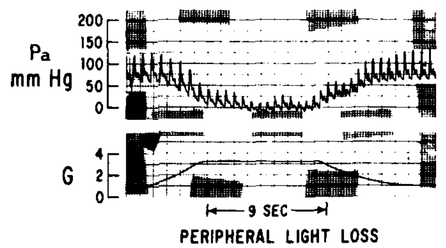

Figure 3. Eye-level Pa responses of humans to increased $+G_z$ exposures resulting in peripheral light loss (10).

It is important to realize, therefore, that a dynamic cardiovascular system is functioning during this initial exposure to $+G_z$; and although the hydrostatic pressures do affect Pa considerably, both higher and lower Pa occur before the "tolerance" Pa develops, thus causing PLL. This temporary rebound phenomenon does indicate an increase in cardiac output, possibly caused by a mobilization of blood reserves from the lungs (12). Nonetheless, venous return is proceeding at a level to support Pa until the occurrence of a G-tolerance criterion at a G-level significantly affected by P_H.

This P_H effect on G tolerance is even significant on an individual subject basis, and has been determined to have an inverse, significant correlation with relaxed G tolerance of r=-0.41, with systolic arterial pressure (Pa) having an additional correlation of r=+0.48. Their combination for individuals has a multiple correlation of r=0.70 (13). On a group basis, with individual variabilities statistically removed, a higher P_H effect is anticipated, and shown to exist (Fig. 2). The physiologic basis, in support of venous-return during reductions in Pa, is venoconstriction of the large veins in the legs and splanchnic region via the carotid sinus baroceptor reflex, and the distensibility characteristics of these veins (14-18). This particular venomotor reflex has been examined in dogs during exposure to increases in $+G_z$, and the response of this reflex has been shown to be directly correlated with the percent reduction in Pa at onset of G (19). The major veins of the body, during short duration exposures to increased venous pressure (because

[1]This value for Pa is calculated from data from Burns and Whinnery (7)--refer to Burton (1) for details about its derivation.

of increased G), tend to be non-compliant and resist blood pooling, thereby supporting venous return during the onset of G. On the other hand, extended duration of increased venous pressure (discussed later in this article) causes reduced blood flow because of "delayed compliance" (14).

Therefore, because of several physiologic functions that support venous return, adequate Pa appears to prevail, at least during lower levels of $+G_z$ exposure, to support this Pa-based model.

Venous return at high G levels, when the AGSM is used by pilots to increase their G tolerance (Fig. 2), has only been studied in miniature swine (20). The increase in the intrathoracic pressure (P_I), during the forced exhalation portion of the AGSM, would impede venous return--but to what extent is unknown.

Venous flow (VF) in the inferior vena cava at the level of the diaphragm was measured at +3, 5, and 7 G_z for 60 s in swine, with and without a pressurized anti-G suit (20). Astonishingly, venous flow was maintained at 5 and 7 G, even during the straining part of AGSM in pigs, and even without the anti-G suit; but VF was much greater during the no strain portion of the AGSM, especially in pigs wearing the anti-G suit (Table 1). As VR declines and can no longer adequately support heart function, heart rate slows with dramatic bradycardia, and loss of consciousness occurs. The importance of the anti-G suit in VR is clearly demonstrated in this study, particularly during sustained G exposures.

Venous return, therefore, can be maintained (not surprisingly) at high G levels where the AGSM is required; and an indicator of adequate VR is heart rate. Venous return does not appear to be a limiting physiologic function at high G.

TABLE 1. VENOUS FLOW (VF) RESPONSE OF THE MINIATURE SWINE TO $+G_z$ STRESS (20)

	$+3\ G_z$				$+5\ G_z$				$+7\ G_z$			
	W/OS	n	WS	n	W/OS	n	WS	n	W/OS	n	WS	n
VF, ml/s												
C	13.7 ± 2.9	8	13.6 ± 3.3	8	15.6 ± 3.0	8	15.6 ± 3.0	8	14.9 ± 3.0	8	15.6 ± 3.4	8
G	8.0 ± 2.7	8	10.8 ± 3.1	8	8.3 ± 2.5	8	10.7 ± 2.8	8	5.3 ± 1.5	8	9.6 ± 1.[illegible]	8
G(S)	-1.4 ± 4.0	7	-0.1 ± 3.1	7	1.8 ± 1.6	7	2.5 ± 2.4	7	3.6 ± 2.8	7	2.3 ± 2.9	7
G(NS)	18.5 ± 7.2	7	22.8 ± 6.0	7	18.7 ± 8.0	7	25.8 ± 4.7	7	15.8 ± 5.9	7	22.1 ± 6.3	7

Data are means ± SEM. W/OS, without G-suit; WS, with G-suit; C, control before $+G_z$; G, mean data over 60 s $+G_z$ exposure; S, mean data during straining maneuver; NS, mean data during no-strain (inspiration).

Intrathoracic Pressure in Support of Pa:

Our original model bases 4 G of protection at 9 G on the P_I generated by the AGSM. We assumed that Pa was increased by 100 mmHg with a P_I of 100 mmHg for a group of individuals who represented a maximum AGSM effort (Fig. 1). That is, we assumed for model simplicity, that the relationship of the intrathoracic pressure (P_I)--that increases during the AGSM and is the basis for increasing Pa--to Pa was 1:1, even though we were aware, because of prior animal and human studies, that the P_I:Pa ratio was more realistically 0.8 (20,21). This compromise did not significantly affect our original model, since we were concerned with "lower" G levels of ≤9 G. However, as we extrapolate our model above 9 G where the AGSM becomes the major modality of G protection, possibly allowing a subject to tolerate 20 G, a more accurate P_I:Pa ratio will be incorporated into the model. That is to say, as the eye-heart vertical distance (h of Eq.(3)) becomes smaller (as the subject is reclined or pronated), G tolerance increases exponentially with an increase in Pa; i.e., 4 G protection results from an increase in Pa of 100 mmHg in the upright subject, whereas reclining that subject to 75° results in eye-heart vertical distance of 150 mm implying that the same 100 mmHg of Pa produces an increase in G tolerance of 9 G. However, the physiologic effect of P_I on G tolerance remains as a simple summation with Pa, so that:

$$G = (Pa + 0.8\ P_I) \cdot d/h \quad (3)$$

where:

P_I = Intrathoracic pressure in mmHg

G, Pa, d, and h are the same as Eq.(2).

Therefore, the following physiologic question arises regarding the model's G-tolerance predictability: Is it possible for a subject to continue to increase the Pa with the support of P_I at these high G levels?

Two variables must be considered regarding the ability of a subject to increase the P_I, with a voluntary effort, in this environment: (a) the ability to develop an inspiratory volume at these high G levels; and (b) the effect of change in posture (supination or pronation) on developing an increased P_I.

First, however, does P_I at the levels required to develop an increase in Pa of approximately 100 mmHg occur in humans using the AGSM? In our original model validation, adequate P_I, as measured with esophageal pressures (P_{es}), did appear to be generated by

subjects during exposures to increased G at different seat-back angles to produce the required Pa (Table 2). However, data showing the maximum P_I, that can be developed by human subjects, were not available.

TABLE 2. ESOPHAGEAL PRESSURES (P_{es}) IN mmHg IN GROUPS OF SUBJECTS (N) AS RELATED TO SEAT BACK ANGLES AND h (1)

Seat ∠	h (mm)	P_{es} (mmHg)	N[a]
13°	334	52.9	3
30°	334	44.8	2
45°	280	40.7	3
55°	250	29.2	2
65°	220	15.3	3
75°	175	16.7	2
45°	280	76.5	2
65°	220	27.8	?

[a]Number of subjects per group.

Recently, maximum P_I was determined in subjects in various postures at 1 G performing an AGSM. Their spine-to-thigh angles ranged from 70° to 105° (four different angles), with a maximum P_I effort by each subject at each angle. Angle did not affect the results that showed the maximum P_I for a group of subjects to be approximately 110 mmHg for the initial strain (Fig. 4). These maximum P_I efforts resulted in increases in Pa of about 80 mmHg, once again showing that the Pa:P_I ratio is approximately 0.8 (Fig. 5). Successive efforts were less effective, indicating that subject fatigue was playing a role in their AGSM ability. The probable role of fatigue on this model is discussed briefly later.

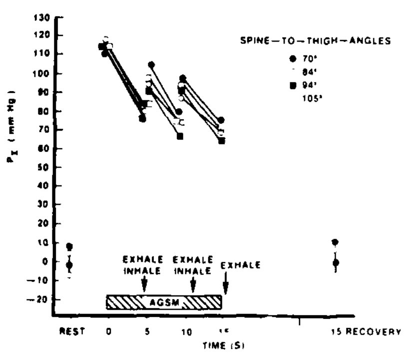

Figure 4. Maximum P_I developed by subjects at 1 G performing an AGSM (22). All subjects wore an uninflated anti-G suit. Three AGSM efforts were performed during the 15-s time period.

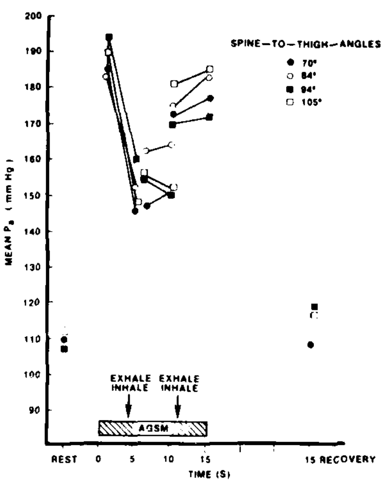

Figure 5. Effect of a maximum P_I (see Fig. 4) on Pa in subjects performing the AGSM at 1 G (22).

Extrapolating G tolerance predictions above 9 G, using our model, has never been previously attempted. At these high levels of G, very little interest appears to have prevailed regarding human G tolerance studies. According to a review of the literature,

only one study has been conducted to determine the maximum G level tolerance possible in a reclined seat configuration (supine $+G_x$) using the AGSM, and no studies have been conducted using pronation ($-G_x$). Wood (23) did report on a study, conducted in 1945 on the human-use centrifuge at the University of Southern California, that had 8 subjects experiencing $-12\ G_x$ without any visual symptoms. The maximum $-G_x$ tolerance of these subjects was apparently never attempted.

Unfortunately, the one $+G_x$ study which used a 75° seat, also used inexperienced subjects, as well as the pelvis-and-legs elevating (PALE) seat that does not reduce the eye-heart vertical distance substantially (6). Consequently, these subjects achieved only a mean G tolerance of 8.4 G using the PALE seat, anti-G suit, and AGSM. This level of G tolerance is easily obtained in the upright seat, using well trained subjects wearing the anti-G suit and performing the AGSM (24). In that PALE-seat study, however, the authors noted that one subject tolerated $+14\ G_x$ for 45 s without any peripheral light loss or "any other undesirable symptoms." It is worth noting, moreover, that, at a 75° back angle with the head extended along the back angle, 10 G is obtained in relaxed individuals as predicted by the model (25).

In considering, therefore, the ability of a subject to perform the AGSM in a high G environment (>9 G), various protective methods must be evaluated, as well as how these relate to increased seat back angles that reduce "h" of Eq.(2).

The relationship between the inspiratory volume (V_I) on P_I, as generated by the AGSM, has been developed and has shown that, for peak pressures above 80 mmHg up to a maximum of 108 mmHg, more than 10% of the maximum inspiratory volume is required (26). However, it is interesting that significant levels (80%) of P_I can be obtained using only 12.5% of the maximum inspiratory capacity of the subject (Fig. 6).

Lung volumes are affected differently by supination or pronation. The former, because of the increased weight on the chest, causes large reductions in most lung volumes so that, at $+8\ G_x$, the inspiratory reserve (IR) is about 25% of the inspiratory volume found at 1 G (27). This relationship between level of $+G_x$ and IR volume is shown in Fig. 7. This sigmoidal function suggests that the reduction in IR, although progressing at higher G levels, is doing so less rapidly than at the mid-G level range of 4-6 $+G_x$, so that an IR of 12.5% is reasonable for high G levels of ≥15 G.

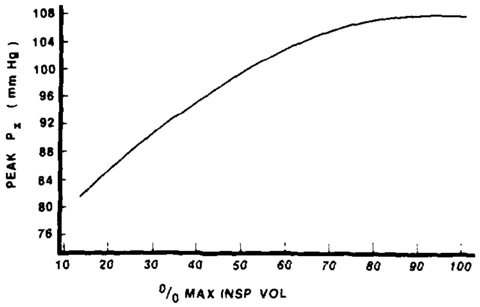

Figure 6. Maximum P_I generated by percent of V_I (26).

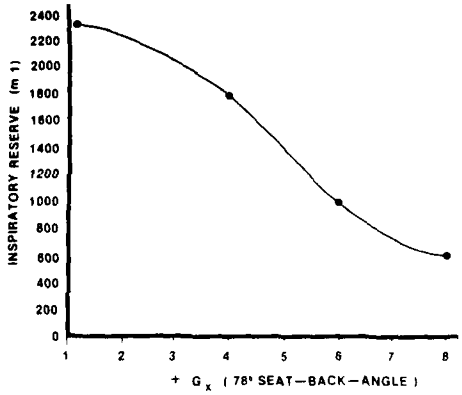

Figure 7. Relationship of inspiratory reserve with 78° back angle. Developed from data from Watson and Cherniach (27).

Cote et al. (26), in their study, found that at an IR of 12.5% the maximum P_I was 80 mmHg; so, by using the same P_I in Eq.(3), a tolerance of 14.8 G is predicted. This G level is the maximum that has been demonstrated on a centrifuge that a human can tolerate in the $+G_x$ vector (4-6). Therefore, as a person is supinated, the reduction in the IR significantly limits the level of AGSM that is possible. We may conclude that, even though a given increase in Pa at greater seat back angles results in proportionately greater increases in G tolerance (Fig. 1), because of this limited ability to do an AGSM, the increase in G tolerance provided by the AGSM at 75° seat back angle remains at about 4 G.

Unassisted PPB, at moderate levels of 2-3 mmHg per G up to 20 mmHg at 8 G, significantly reduced the decrease in IR found at $+8\ G_x$. Therefore, instead of only 26% of 1 G values, IR was 41%, yielding an increase in projected P_I of 12 mmHg. With an h of 150 mm, this would result in an expected tolerance increase of 1 G (Eq.(3)). Greater benefits might be possible with increased levels of PPB, including the use of chest counterpressure (assisted PPB). Recent studies with subjects positioned upright experiencing $+G_z$ have shown tolerances up to 70 mmHg of assisted PPB, although 50 mmHg was considered the most beneficial (28). Fifty mmHg of assisted PPB is expected to increase $+G_z$ tolerance by

approximately 2 G (Eq.(3); Fig. 1). Recently, test flights in both the F-15 and F-16 at the Air Force Flight Test Center (AFFTC), Edwards AFB, have demonstrated that this level of assisted PPB increases $+G_z$ tolerance (as subjectively evaluated by pilots) by 2 G.

Pronation does eliminate these large reductions in lung volumes as h is reduced (29). The maintenance of a large inspiratory reserve, therefore, would allow the subject to perform an effective AGSM, thus suggesting that extremely high G tolerances (such as predicted in Fig. 1) could be obtained with an h of 150 mm. A shorter h, relative to seat back angle, is possible as a human is pronated (as opposed to supination) because of the eye-heart vertical relationship (Fig. 8). During the beginning of reclining, h actually increases, whereas h becomes shorter immediately at the initiation of pronation (30). We must assume, at this time, that our model is valid regarding h relationship to G tolerance, regardless of the direction of the reclining subject--whether supine or prone.

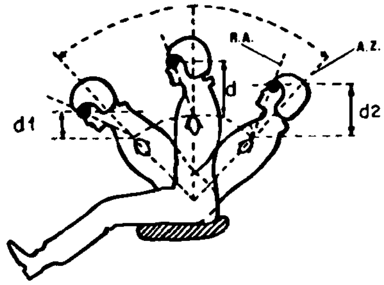

Figure 8. Change in eye-heart vertical distance (d) with supination (d_2) or pronation (d_1). RA'= retiral - aortic line; and AZ = anatomical z (longitudinal) axis (30).

Since maximum G-tolerance studies with subjects in the prone position have never been performed; the relationship between this position, anti-G suit inflation, and AGSM with or without assisted PPB, is unknown. Generally, studies in these more reclined or pronated postures have been concerned only with "relaxed" tolerances, usually without the anti-G suit. In order to validate this model above 9 G, carefully planned studies defining the roles of various G protective systems (as each acts alone and interacts with the other systems) must be conducted. Only then can we define the maximum G levels possible for humans using proven G protective methods. However, our present level of understanding suggests that man can tolerate 15 G with a reduced h. Consequently, it is doubtful that any aircraft in our lifetime will perform at a maneuvering level at which the pilot, if properly protected by using known anti-G protective systems, will limit aircraft performance.

G-INDUCED FATIGUE

Until recently, tolerance to increased G had a single dimension that was only G level. The amount of time (duration) that a pilot could tolerate an increased G environment was not considered. Even today, pilot limitation to the G environment is recognized primarily as a G-level phenomenon. The importance of fatigue and the interest in its relation to G level tolerance have increased recently, however, because of the capability of operational high performance aircraft that can sustain a high G environment (9 G) for protracted periods (31-33).

Fatigue, as an acceleration tolerance criterion, is usually measured on the centrifuge using a stylized aerial combat maneuver (SACM) G profile. This profile maintains the same alternating levels of G until the subject can no longer continue because of exhaustion (31; Fig. 9). Since fatigue can clearly limit human tolerance to the high G environment, is it then possible for duration tolerance (fatigue) to make the pilot the limiting factor in high performance aircraft? The answer, as with the presumed G level tolerance limiting factor, is a resounding no!

There are four reasons why pilot fatigue tolerance can be significantly increased: (a) G-level tolerance and G-duration tolerance are tightly coupled, so that increasing G-level tolerance increases G duration tolerance; (b) a reduction in the effort required to increase the P_I (such as with assisted PPB) increases G-duration tolerance; (c) an improved ability to increase P_I (such as with anaerobic muscle-strength physical conditioning) increases G-duration tolerance; and (d) improved physiologic support with an improved anti-G suit also increases G-duration tolerance. The last three increase G-duration tolerance without necessarily increasing G-level tolerance; i.e., thus demonstrating that G-duration is a different tolerance dimension.

G-level-duration Tolerance Coupling:

Burton and Shaffstall (31) reclined subjects to 65° supine, and exposed them to the SACM until fatigued (Fig. 10). A direct coupling between relaxed G-level tolerance

and G-duration tolerance is clearly demonstrated. Therefore, as G-level tolerances are increased with advanced protective methods (as discussed previously in this article), G-duration tolerance will also increase. On the other hand, as subjects become fatigued, their ability to perform an AGSM is diminished, so their G-level tolerance is reduced. This reduction in G-level tolerance has been estimated to be approximately 1 G for each 30 s of ACM (33).

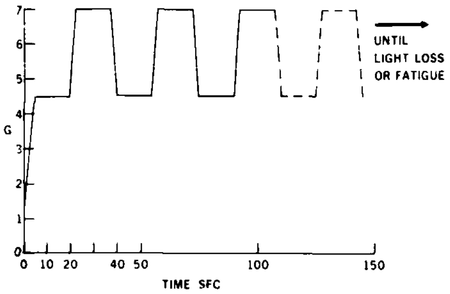

Figure 9. Simulated aerial combat maneuver (SACM) used on the centrifuge to quantify G-duration tolerance (31).

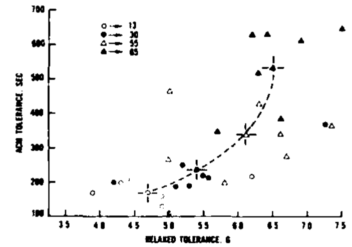

Figure 10. Relaxed G tolerances are compared with SACM tolerances at four seat back angles (31).

Improved Methods to Increase P_I:

Assisted PPB at 30 mmHg has been shown to increase G-duration tolerance to the SACM by 35% (34). Higher levels of assisted PPB of 50-70 mmHg increased G-duration tolerance to a $+5_z$ to $+9_z$ SACM by 110% and 72%, respectively (28). Additionally, the G-tolerance coupling between G-level and G-duration is particularly evident in assisted PPB. As discussed earlier in this text, assisted PPB gave pilots what they considered was a "2 G" advantage that significantly reduced their fatigue level.

Improved Ability to Increase P_I:

Physical conditioning, by improving anaerobic capacity and muscular strength, has been shown in three separate studies to increase G-duration tolerance--in one study by as much as 77% (35-37). The Air Standardization Coordinating Committee (ASCC), Working Party 61 is in the process of adopting an Advisory Publication 61/103I "Physical Fitness and G Tolerance" that proposes methods of strength training and increasing anaerobic capacity for pilots to increase their ACM tolerance. The U.S. Air Force (USAF) and U.S. Navy (USN) are coordinating efforts to develop a common physical conditioning regime. In a recent field study, USN pilots found anaerobic and muscular conditioning particularly beneficial in improving their ACM tolerance (39). The USAF encourages pilots of high performance aircraft to participate in muscle-strength building activities.

Improved Anti-G Suit:

The anti-G suit was modified by increasing the leg support with uniform coverage of the entire leg, instead of the "spotty" bladder leg pressurization of the operational anti-G suit. This suit modification increased SACM tolerance 133% (Fig. 9)--subjects were now capable of 497 s of the SACM, as compared with only 213 s with the standard anti-G suit (38).

During the SACM, heart rates in subjects with this suit also were significantly reduced. Since the only modification in this suit was improved support for venous return, this physiologic parameter in the development of fatigue during the SACM has become a very important consideration in anti-G suit design.

The physiologic importance of venous return during prolonged exposures to high G levels is much greater than during short duration exposures to G. For this reason, the leg support of the anti-G suit in increasing "relaxed" G tolerance is insignificant, but leg pressurization is most effective during high sustained G (HSG) exposures in significantly reducing heart rate (39).

Good evidence shows that venous return, because of blood pooling, is G-tolerance limiting during sustained exposures to high G--a physiologic problem that apparently is not an issue during short duration exposures to G. This phenomenon appears to be caused by "delayed compliance," induced by venomotor fatigue, visco-elastic effects in the venous walls and, possibly, recruitment of peripheral vessels due to the change in pressure (14). The delayed compliance response accounts for a significantly greater volume change than the rapid elastic distension that occurs at the initiation of increased G.

In support of this venous system, particularly during the delayed compliance response which tends to reduce venous return, adequate venous wall pressure support is required and can be managed with a uniform pressure anti-G suit. This concept has now

been incorporated into a prototype anti-G suit, using a single bladder design; and encouraging results are reported by the laboratory.

CONCLUSIONS

At the present time, we must assume that the pilot with current operational protection is probably the limiting factor in high performance aircraft. This assumption was demonstrated in a recent flight test of assisted PPB at the Air Force Flight Test Center (AFFTC), Edwards AFB, California, where pilots of the F-15 or F-16 were reluctant to fly aerial combat maneuvers (ACM) against each other unless they both had assisted PPB. The pilots thought they had a 2-G advantage, and were much less fatigued with this improved anti-G protective system: assisted PPB.

Fortunately, the pilot need not be the limiting factor, as that scenario clearly demonstrates. In this article, we have shown that pilot acceleration protection technologies are apparently available to potentially extend tolerance into the 12 to 15 G regime. Developing and incorporating these technologies into operational systems will produce a real advantage in air combat as currently conceived. But in this regard, more time is needed, because the basis for G protection is reducing the eye-heart vertical distance--an undertaking that will require a serious commitment by engineers who design and build airplanes. That commitment will no doubt be, for them, a significant challenge; but increased aircraft performance, enabled by improved pilot performance, should amply reward their efforts.

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A MODEL TO PREDICT VISUAL PERFORMANCE AT THE MAN-DISPLAY INTERFACE IN THE COCKPIT

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SUMMARY

This paper summarises some of the problems which are typically encountered when viewing displays in the military cockpit. It is suggested that design and development of display configurations can be made quicker, cheaper, and more effective than present methods by using mathematical models of the man-display interface to predict visual performance. The requirements for such models are discussed. A state-of-the-art model which has been developed at British Aerospace is reviewed. The model comprises spectral manipulation routines to calculate how the emission spectrum from a display is modified before reaching the eye, together with a psychophysical vision model which provides an objective measure of visibility. The benefits of using such a model are described. Finally, suggestions are made for future work to extend the present models. A detailed description is not given of the calculations in either part of the model but further information may be obtained from the references or by contacting British Aerospace, Sowerby Research Centre.

1. INTRODUCTION

British Aerospace (BAe) is a major producer of civil and military aircraft, guided missile systems for air, land and sea use, and also satellites and space platforms. The company thus has a wide and varied interest in many types of displays. Of particular importance are displays for use in the military cockpit. For a number of years work has been carried out within the Military Aircraft Divisions and at BAe's corporate research centre (the Sowerby Research Centre (SRC)) with the aim of improving methods to solve problems with the visual perception of displays in cockpits.

Colour displays form an integral part of modern fighter cockpits. Complex information has to be presented so that it can be assimilated easily and acted upon. Various forms of coding are used, the dominant ones being shape, size and luminance. Colour is mainly used to de-clutter displays. To gain full advantage of colour displays and avoid their use for purely aesthetic reasons, the benefits of using colour need to be quantified.

There are many problems with displays in cockpits. In addition to the physical problems of size, weight, power consumption and reliability, display legends must appear legible, clear, and of a required colour in very high ambient lighting conditions. They must also perform satisfactorily in low ambient conditions without adversely affecting vision through night vision goggles.

At British Aerospace we believe that the way forward lies in modelling the man-display interface mathematically and attempting to define quantitatively the performance required of it. A better understanding of visual performance and efficient use of modelling techniques will reduce time and costs for equipment development and improve the man-display interface.

2. BACKGROUND

A pilot must be able at all times to interface effectively with both the outside world and the various displays within the cockpit. His attention will be divided visually between the two as the situation demands. It is therefore essential that neither environment inhibits his view of the other, i.e. they produce the same degree of relative visibility. When flying during the day the external environment will tend to dominate and conversely at night it is the cockpit displays which will appear bright to the detriment of the pilot's perception of the world outside.

Clearly, neither the pilot's vision system nor the external ambient conditions can be changed, therefore it is the cockpit display configuration (including the complete display environment and viewing aid or visor) which must be designed to compensate for the limitations of the pilot's visual capability and those imposed by the ambient lighting conditions. The real world natural ambient illumination is both too varied and too complex for every condition to be considered in the design of displays. A compromise solution is thus sought whereby a display's performance is modelled in limiting ambient conditions; if it is found to be acceptable then it is assumed to perform satisfactorily under other conditions.

Practical flight experience has identified two high ambient steady state limiting cases when display performance will be most severely tested. These are both associated

with a low elevation bright solar disc. The first is when flying away from the sun ('sun rear') and direct solar illumination reflected from the display face causes a reduction of luminance contrast and desaturation of colours on the display. The second case is when flying towards the sun ('sun forward') as direct solar glare reduces the pilot's perceptual capability, thus degrading the appearance of the display.

A common way of alleviating the problem of the sun rear case is to place in front of the display a contrast enhancement filter with an anti-reflection coating. This may be a narrow bandpass absorption filter matched to the display's spectral output so that, ideally, it absorbs all wavelengths incident on it apart from those emitted by the display. For the sun forward case the problem of solar glare on the pilot's visual perception can only be overcome by a very bright display output, i.e. if a contrast enhancement filter is used it must have a high transmission.

Low ambient conditions pose different problems. External vision is enhanced by the use of night vision goggles (NVGs) which amplify electromagnetic radiation between 400 and 900 nm and reproduce the scene as a single phosphor image. Using NVGs the operational limitation on the aircraft to perform a low-level, high-speed role can be extended from dusk or bright moonlight down to the starlight environment. NVGs have a limited depth of focus, therefore cockpit displays must be viewed with the naked eye. The brightness of the NVG image will be too great for the pilot to achieve scotopic (rod) vision, so displays must be sufficiently bright to be clearly legible photopically, though not so bright as to cause flare in the NVGs. Unfortunately, just controlling display luminances is not sufficient, as emissions from displays at wavelengths to which the NVGs are sensitive can produce unwanted glare and wash out the reproduced image of the external scene. Display outputs must therefore be carefully matched to NVG performance.

The requirements for the three cases (sun rear, sun forward, and night) are thus contradictory and display/filter combinations which satisfy one requirement may not perform well in the others. A compromise is needed which will perform reasonably well in all conditions. Mathematical modelling enables the design engineer to evaluate the various compromise options in an objective way and find the optimum solution available for a specific case, judging performance against cost.

Without an objective measure, the engineer must base his design on the last generation of displays and his personal experience. The prototype display configuration enters an iterative subjective evaluation loop as it is assessed by experienced aircrew, reviewed and modified, then submitted for reassessment. This method is tried and tested and generally produces some level of acceptance, although it can be both time consuming and expensive. The other main problem with this technique is that, as it involves subjective evaluation, it is obviously dependent on the visual acuity and experience of the pilots performing the assessment. If the system can be modelled for the average pilot, including observer variability, and an objective 'figure of merit' provided, then it should be possible to increase the probability of first time acceptance, i.e. reduce the number of iterations by dismissing unsuitable configurations without the need for repeated costly flight trials.

The man-display interface essentially consists of two parts which must be represented mathematically. The first covers all physical interactions with the object's emission spectrum from leaving the display to entering the eye. The second, psycho-physical, part deal with the visual interpretation of this spectrum within the eye. Of these two, the physical part is easier to model as it consists of well-defined calculations for the various spectral paths leading to the eye. The psychophysical part presents more of a problem. The CIE (International Commission on Illumination) has defined equations for evaluating the colour difference between an object and its immediate background [Refs. 1 and 2]. One of the recommended colour spaces for colour difference calculation is the CIELUV space. The total difference ΔE^* between two colours in the CIELUV space is defined as the vector distance between them:

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{\frac{1}{2}} \qquad (1)$$

where: L^* is psychometric lightness;
u^* and v^* are components of perceived chroma.

Unfortunately, the presently available equations are only applicable to small colour differences and large uniform objects and are therefore not relevant to most real tasks, which may involve small, irregular, brightly coloured objects on cluttered backgrounds. The size of the object is not given as a variable, although it obviously has an effect on visual performance. There are several other important factors which will affect the perception of the object, including the quality of display and the type and complexity of the task being performed, none of which are included in the simple CIE equations. To include all of these factors requires a sophisticated vision model.

For a number of years the Sowerby Research Centre has been developing and refining models to predict thresholds of visual performance for a variety of tasks. The models can handle a wide range of visual tasks from the detection of simple stimuli on uniform backgrounds to form perception and visual search in noisy or cluttered background scenes. The modelling is based on the results of laboratory studies and field trials, and the known physiology of the eye.

One of the models, ORACLE [Ref. 3], has been developed as a threshold model for

stimuli with simple profile structures and little internal texture. ORACLE provides a probability of detection for an object by comparing retinal cone responses for the object and its immediate background. A detailed description of the ORACLE model is beyond the scope of this paper but details of the equations may be found in References 4 and 5.

As well as using the basic information about an object (luminance contrast, chrominance difference, size and shape), ORACLE takes into account other factors such as:

(a) Foveal and peripheral performance - This is based on a comparison of receptor responses across the regions of maximum illuminance gradient of the image, i.e. along the object's perimeter. ORACLE models performance based on the length and strength of the perimeter imaged on the retina.

(b) Mean scene luminance - This determines pupil diameter, which controls the amount of energy falling on the retina.

(c) Search - The modelling of peripheral detection allows search performance to be predicted.

(d) Observer variability - Statistical variations due to normal observer populations are included.

(e) Object movement - It is possible to model the effects of retinal image motion on performance.

(f) Image quality - ORACLE can model the effects of viewing imperfect images blurred by optics or discretely sampled by noisy, raster type displays. A visual efficiency term is calculated which relates image quality of the total system (including eye) to that of the eye alone. Image quality is defined in terms of a modulation transfer function (MTF) varying with spatial frequency.

(g) Complexity of task - The most simple visual task is the detection of an object against a uniform background. For most real tasks some degree of discrimination must be made between the object and potentially confusable background objects. This is included in the model by looking at detection of a part of the object. Increasing levels of task complexity are modelled by considering smaller fractions of the target perimeter, as more detail must be resolved.

(h) Spatial and temporal integration - ORACLE models the effective interaction of the spatial and temporal integration of a display with that of the visual system. This allows consideration of factors such as phosphor persistence, raster decay properties and refresh rates, random and systematic noise, sampling pitch, spot profiles, and display MTFs in vertical and horizontal directions.

ORACLE was originally developed as a threshold achromatic model and this is now well validated, however, it has only recently been extended to consider both colour and suprathreshold objects. Thus it is still undergoing validation in these areas and the data to test it fully are only now being obtained. Although ORACLE has been used successfully to model various optical sights, a version which considers the use of NVGs is not available at present. The present form of ORACLE is thus not an ideal, fully comprehensive vision model, but it is representative of the state-of-the-art and is a versatile and useful design tool.

For complex stimuli (highly textured objects) a computer simulation, called VISIVE [Ref. 6], is used to model the known early interactive neural processes in the retina and striate cortex. VISIVE provides a method of characterising or coding stimulus information in a similar manner to that which is believed to be available for interpretation in the brain. The modification of the stimulus by VISIVE can be used as an objective input to ORACLE. The amount of processing performed by VISIVE is quite considerable which means that it can only be implemented on a mainframe computer.

A simple empirical psychophysical model has already been shown to be useful in assessing the performance of displays in the cockpit. This model is based on the concept of the 'Perceived Just Noticeable Difference' (PJND) [Ref. 7] and is similar in approach to RAE Farnborough's 'IDEAL' display design tool [Ref. 8]. 1 PJND is the threshold colour difference (composed of both luminance and chrominance differences) required to just detect an object from its background. Above this threshold condition (which may be achieved by an infinite variety of luminance and chrominance combinations), the colour difference between the foreground and background is equivalent to a number of PJNDs greater than one.

$$\text{No. PJNDs} = [(\text{No. LJNDs})^2 + (\text{No. CJNDs})^2]^{\frac{1}{2}} \qquad (2)$$

where: No. LJNDs is the number of luminance just noticeable differences $= \dfrac{\log\ (\text{Luminance ratio})}{\log\ (\text{Threshold luminance ratio})}$

No. CJNDs is the number of chrominance just noticeable differences $= \dfrac{\text{Chrominance contrast}}{\text{Threshold chrominance contrast}}$

Chrominance contrast is measured in the CIE 1976 UCS diagram. Threshold contrasts for

both luminance and chrominance are functions of object size and background luminance.

Assuming that suprathreshold visibility increases with CIE colour difference, then for a greater number of PJNDs, a greater degree of visibility will be expected. Thus it is possible to relate visibility to a directly measurable quantity. Experiments using calibrated stimuli in a representative environment have determined ranges of acceptable PJNDs for various tasks. The model is limited in terms of the object sizes to which it is applicable and also assumes that the CIE 1976 UCS is uniform.

The PJND concept has been combined with the physical manipulation of spectra to provide a simple system model. This model is being used for designing display systems in a number of aircraft (Tornado, Jaguar, Harrier, EAP). However, it is severely restricted by the limitations of the simple PJND approach. The model introduced in this paper extends this basic model, making it more flexible and generally applicable by adding a version of ORACLE. The use of such a versatile and comprehensive model incorporated with the display system and environmental model greatly extends conventional and recommended methods for evaluating colour and luminance differences. In particular, such a model will allow display characteristics and other components of the man-display interface to be optimised as functions of object size and shape, peripheral viewing angle, observer task etc.

3. REQUIREMENTS OF A MATHEMATICAL MODEL

Figure 1 shows the basic elements required for a man-display interface model. The first is a display model to calculate the spectral output of a display for an object and its background. The second is a physical model to calculate how the display output is altered in both luminance and chromaticity before reaching the eye. A vision model is then needed to calculate the perceived difference between the object and its background. Finally, this must be interpreted by cognitive user model, taking into account workload, task, experience etc., before an evaluation of the system can be made. Not all elements of this system model exist at present. In particular, a model which can account for the cognitive aspects of vision is not available, and vision models are generally at an early stage of development. Until suitable cognitive models become available it will be necessary to use empirical metrics to evaluate display systems (for example, the CIE system, the PJND method or empirical use of ORACLE output).

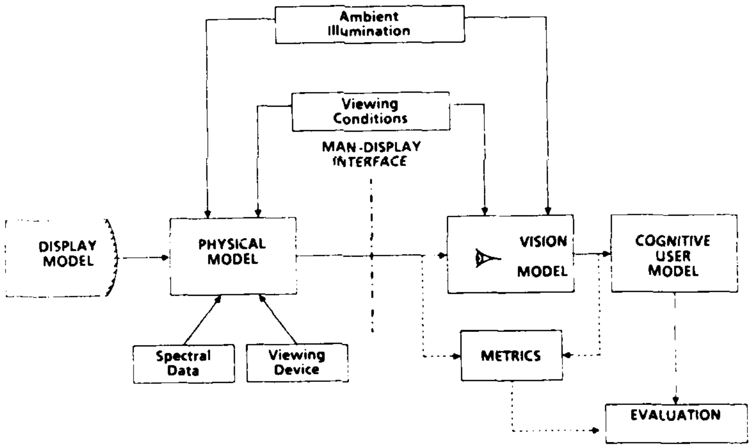


FIGURE 1. SCHEMATIC OF MAN-DISPLAY INTERFACE MODEL

For a man-display interface model to have as wide an application as possible it should cover the complete range of cockpit displays, including emissive (ranging from light emitting diode or incandescent lamp captions to multi-function full colour cathode ray tubes), reflective (liquid crystal displays) and transmissive (head-up and helmet mounted displays) technologies.

The model should consider the environmental extremes of day-time and night-time viewing. For these two conditions performance requirements must be specified in different ways. In high ambient conditions a measure is needed of the relative visibility of an object (e.g. display legend) with respect to its immediate background. At low ambient it is important that displays are sufficiently bright to be viewed photopically with the naked eye, whilst not being so bright as to saturate the NVGs. The critical measure is thus the ratio of the perceived brightness of the object as viewed with the naked eye to its perceived brightness viewed through NVGs.

A versatile form of the model would be a program written in a high level language, composed of programming modules and implemented on a common micro-computer. Th[illegible] would

enable the model to be widely available, portable, and easy to update as new data become available or additional/alternative specifications are established. In addition, input requirements should be clear, and preferably absolute measurement data derived from the display or the component parts making up the interface, while outputs must be easy to interpret and compare with specification requirements, e.g. by providing a table of typically acceptable model visibilities for various tasks.

4. STRUCTURE OF THE MODEL

The model is implemented on an IBM PC. It is programmed in Pascal, which supports a suitable modular form to allow easy updating without disrupting the basic form of the model.

The two halves of the interface (shown in Fig. 1) are treated separately; the display-to-eye part by a physical model composed of spectral calculations and the eye's interpretation by ORACLE.

Whilst effort has been given to making the model reasonably straightforward to use, with simple menu-based options, it is not an 'expert system' and does require a reasonable amount of experience of this sort of problem to be used effectively.

5. PHYSICAL MODEL

This model calculates how display emissions are modified before reaching the pilot's eyes, thus establishing the spectral power distributions representing the display foreground and background as they enter the eyes. At present the model is limited to consideration of emissive devices only, however, it is planned to extend it to include both reflective and transmissive displays. Although capable of considering any ambient illumination condition, the model is configured to represent only the two limiting high ambient cases, sun rear and sun forward. Table 1 shows the conditions associated with these cases in the Tornado cockpit.

Table 1. High ambient limiting conditions for Tornado

	Sun Rear	Sun Forward
Solar elevation	30 deg	15 deg
Eye illumination	12,500 Lux	109,000 Lux
Display illumination	94,000 Lux	6,500 Lux
Helmet visor	Up	Down

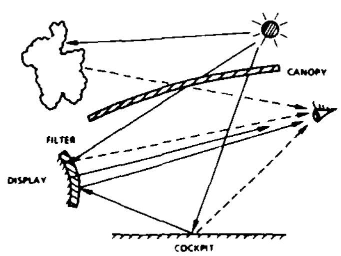


FIGURE 2 SUN REAR SCHEMATIC

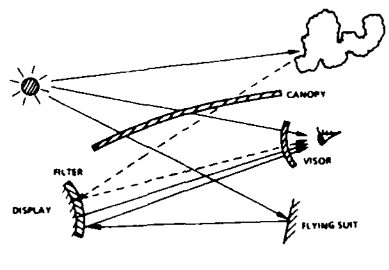


FIGURE 3 SUN FORWARD SCHEMATIC

It is theoretically possible to consider every conceivable spectral path, however, to simplify programming the model has been limited to the primary paths only. Figures 2 and 3 show schematics of the spectral light paths involved with these two conditions. The calculations involve modelling transmission of the object and background spectra through filters, the inclusion of glare and reflections from both the display face and around the cockpit. Each of these simple stages is performed by a separate programming module, to allow easy reconfiguration by replacing, adding or removing modules. One module calculates the resultant spectrum after being transmitted through a filter and another calculates how a spectrum is modified by reflection from a surface. Other modules perform simple arithmetic operations such as addition or multiplication. When looking at the effects of glare, both specular light from the solar disc and diffuse illumination from the sky dome must be considered. Both of these contributions are included in a glare module, using equations based on those in Reference 9. Figure 4 shows an example block diagram containing calculation modules for the sun rear case (see also Fig. 2). Note that emission spectra are normalised to give a luminance of 1 Cd/m² when stored and therefore need to be multiplied by their respective emission levels before use. Output, in the form of calculated luminance and chromaticity coordinates, may be obtained at any point in the calculation, allowing termination of the model before completing the full calculation. This may be a useful feature when optimising a single part of the interface, such as a filter.

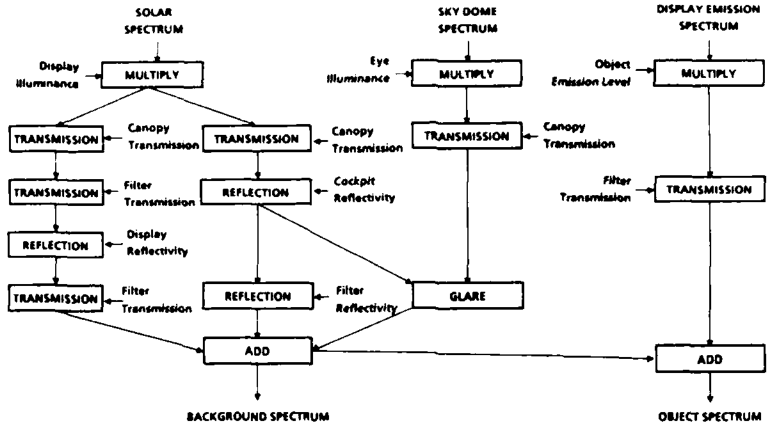


FIGURE 4. BLOCK DIAGRAM SHOWING PRINCIPAL CALCULATIONS FOR SUN REAR CONDITION

The model assumes that the pilot will use his helmet visor to gain relief from direct solar glare in the sun forward case. The display arrangement can be set up to represent either displays in the head-up area, where solar glare will be most disruptive, or in the general head-down position, where glare will be less critical. It should be noticed that specular reflections of the pilot's flying suit may be caused on the display face, having implications on the colours worn.

The required spectral inputs are:

(a) Emission source.
(b) Solar radiation (defined in program).
(c) Diffused sky radiation (defined in program).
(d) Transmission of canopy (defined in program).
(e) Diffuse reflectivity of display.
(f) Specular reflectivity of display.
(g) Transmission of contrast enhancement filter (if used).
(h) Transmission of helmet visor (defined in program).
(i) Reflectivity of flying suit (defined in program).
(j) General reflectivity of cockpit (defined in program).

An additional input is the angle subtended at the eye between the horizontal and the display. This specifies where in the cockpit the display is positioned and hence the effect of glare.

The main outputs are the spectra for the object and its background which are used as input for ORACLE. As a secondary output, the number of PJNDs between the object and its background is calculated (see Section 2), which may be used as an indication of display performance, though for a more rigorous evaluation ORACLE should be used to calculate visibility.

6. PSYCHOPHYSICAL MODEL, ORACLE

The version of ORACLE which has been implemented in this model is for basic object detection and visibility calculation. It does not include such refinements as object motion or the consideration of optical sights (though these may be include later if the need for it is identified).

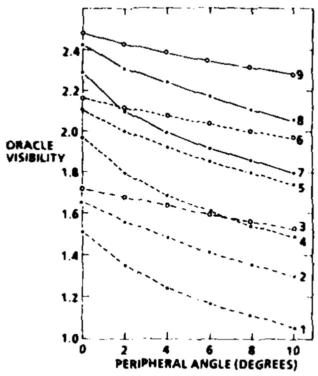
The inputs to the model are:

(a) Object and background spectra.
(b) Peripheral angle (less than 2 degrees for foveal detection).
(c) Mean scene luminance.
(d) Size of object (in milliradians, mr, subtended at the eye).
(e) Image quality.
(f) Task complexity.
(g) Time for detection (there are two values depending on whether the observer is searching the scene or fixating a point.

Further information on these parameters is given in Section 2.

The output appropriate to the perceived visibility of cockpit displays is not a probability of detection (as all object stimuli should be well above threshold), but ORACLE's measure of suprathreshold visibility, which is related to the ratio of measured suprathreshold contrast with threshold contrast. The program is written to give graphs

and tables of predicted visibility against peripheral angle. Using this information it can be easily seen at which angle a particular configuration's performance may fail below specification. At present there is little data available giving ranges of acceptable ORACLE visibilities for various real tasks. To use the model effectively these ranges must be defined.



KEY

	Object Luminance (Cd/m²)	Area (mr^2)	Aspect Ratio
1	200	44.9	1:1
2	200	88.1	8:1
3	200	284.1	1:1
4	500	44.9	1:1
5	500	88.1	8:1
6	500	284.1	1:1
7	1000	44.9	1:1
8	1000	88.1	8:1
9	1000	284.1	1:1

FIGURE 5. EXAMPLE MODEL OUTPUT SHOWING VARIATION OF ORACLE VISIBILITY WITH PERIPHERAL ANGLE

Figure 5 shows curves obtained for some hypothetical cases. The lines show the variation in visibility of a plain amber caption plotted against peripheral angle up to a maximum angle of 10 degrees. Three object luminance levels and three areas (including two aspect ratios) for the caption are shown. As might be expected, greater visibilities are predicted for larger sizes and higher luminances. It can be seen that the fall-off in visibility with peripheral angle becomes less rapid as object size increases. Suppose that a minimum required ORACLE visibility of 1.8 has been specified: from Figure 5 it is clear that none of the low luminance captions (lines 1, 2 and 3) would be suitable and that all of the high luminance captions (lines 6, 7 and 8) would be acceptable when presented within 10° of the instantaneous point of fixation. Similarly, the largest medium luminance caption (line 6) could be used out to 10°, but the small and medium sized medium luminance captions (lines 4 and 5) would fall below specification at 2° and 8° respectively.

7. BENEFITS OF MAN-DISPLAY INTERFACE MODEL

The model can be run repeatedly very quickly so many combinations of display phosphor and contrast enhancement filter can be assessed easily, rapidly, and hence very cheaply. Of course, there is still a need for testing by aircrew in representative environments and this will remain an important design stage, but, if objective specifications have been achieved, the system should be close to an acceptable solution.

The use of this model will allow many more display configurations to be tested than it would be practically feasible to assess by flight testing with aircrew. Innovative ideas can be evaluated at the initial design stage and, if thought to be of value, can be developed with the minimum of risk. Hence, it will enable designers to make better use of available technologies. Another major use of the model will be in the drawing up of equipment specifications. Once the requirements for a system have been defined in terms of working conditions, user tasks and necessary information to be conveyed, the specification can be given in terms of an objective measure of minimum visibility.

8. THE FUTURE

The model covered in this paper represents the state-of-the-art in display and vision modelling, but there is still work needed to achieve all the requirements set down in Section 3.

The vision model, ORACLE, is under continual review and extension. Presently experiments are being carried out to provide validation data for the colour aspects of ORACLE and to investigate its suprathreshold performance. Preliminary results of one current experiment, looking at suprathreshold luminance contrasts in high ambient conditions, show very encouraging correlation between ORACLE's predicted visibilities and experimentally measured relative conspicuities (see Fig. 6). The method used in this experiment was by paired comparison of two simultaneously displayed objects on a computer controlled display. The objects used were rectangles of different size and aspect ratio. Two levels of ambient illumination were used. It is clear from the data in Figure 6 that objects of varying luminance contrast, size, and aspect ratio under different ambient illumination conditions can be accommodated by ORACLE. These results confirm that ORACLE is a suitable model for optimising display configuration components in aircraft cockpits, where it is necessary to judge objectively the combined effect on visual performance of

such parameters. Other work is being carried out to produce a module for ORACLE to look at the effect of NVGs on observer performance.

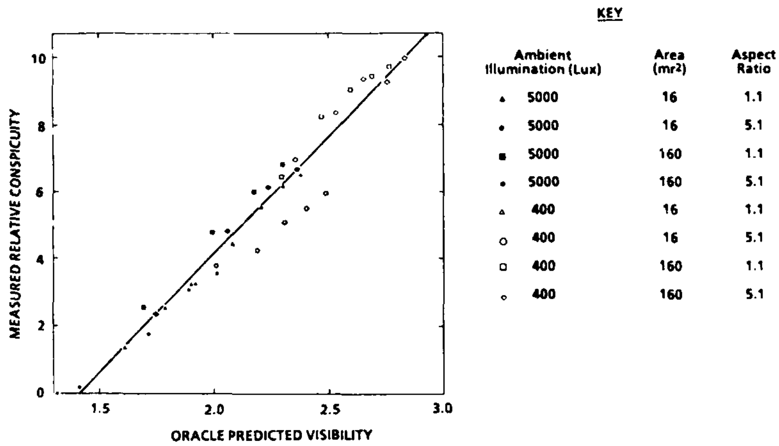


FIGURE 6. PRELIMINARY RESULTS OF EXPERIMENT SHOWING CORRELATION OF MEASURED RESPONSE WITH PREDICTED VISIBILITY

The physical model is presently limited to emissive displays. Work is therefore needed to make it applicable to a wider range of display types, including coloured flat panel displays. To consider a different type of aircraft presently requires the model program to be edited, as the data used in the equations for manipulating spectra vary with different aircraft. A menu selection for aircraft type could easily avoid the necessity of changing the program at code level.

A possible future form of the model could be an 'expert system' allowing the design of a complete display system and the specification of any particular requirements for visual performance. The model could automatically iterate different display/filter combinations to find the optimum solution(s).

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- PILOT WORKLOAD ASSESSMENT - A FLIGHT TEST APPROACH

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SUMMARY

This paper describes the flight test methodology that was successfully used to assess the effect of the integration of a fighter aircraft and a specialized sensor augmentation system on pilot workload and single-seat effectiveness. This methodology also permitted collection of subjective data pertinent to the issues of cockpit controls and displays, situational awareness, task complexity, survivability and safety. Two different subjective workload metrics, supplemented by structured interviews, formed the basis of the data collection procedure. One metric was the Subjective Workload Assessment Technique (SWAT), developed at Air Force Aerospace Medical Research Laboratory (AFAMRL), and the other metric was a modified Cooper-Harper-type scale that was tailored for the project with the inclusion of a performance factor.

The test method mandated that each pilot qualitatively estimate attack performance according to prescribed parameters and then use both metrics to assess his perceived workload. Because we had trained the pilots on the subjective methods to be used during the data collection phase, the pilots were generally very comfortable with providing the workload assessments real time (immediately following task accomplishment). To elaborate on the ratings and related comments, extensive reviews and discussions of onboard video were accomplished after flights among pilots and human factors engineers. This method culminated in a detailed picture of the integrated system with the pilot as the key system operator, with particular emphasis on the pilot's overall workload for mission performance.

INTRODUCTION

This paper summarizes the methodology recently employed to assess systems integration and pilot workload during flight tests at Edwards Air Force Base, California. The tests involved the integration of the pilot with the Low Altitude Navigation and Targeting Infrared System for Night (LANTIRN) and the F-16 fighter aircraft manufactured by General Dynamics. The test aircraft were two F-16B aircraft and one F-16A modified with F-16C/D avionics systems.

The LANTIRN System is a revolutionary new system that consists of a Navigation Pod (NVP), a Targeting Pod (TGP) and a Wide-Angle Raster (WAR) holographic Head-up Display (HUD). This system was designed to provide pilots with the ability to navigate at low altitude and manually follow and avoid terrain while operating under (and to a limited extent through) the weather, both day and night. LANTIRN literally "opened up the night window" for realistic tactical warfare. As a result, it was Tactical Air Command's highest priority test program at the time of this test. Additionally, the system was designed to facilitate pilots' abilities to find and attack a variety of interdiction and tactical targets using conventional, self-designated laser guided and stand-off, launch, and forget weapons in a single-seat aircraft.

The NVP included a Forward-Looking Infrared (FLIR) system composed of a Fixed-Imaging Navigation Sensor (FINS) and a Terrain-Following Radar (TFR). Together, these provided a day or night, under-the-weather, low altitude terrain following (TF) capability. The pilot interfaced with this pod through the WAR HUD and controlled pod functions from the cockpit via the multifunction displays (MFDs) and the up front controls (UFC). The TGP included a target acquisition FLIR (TAF), an image tracker, a stabilization system, a Missile Boresight Correlator (MBC), and a Laser Designator/Ranger (LDR). These allowed a day or night, under-the-weather target acquisition and recognition and first pass weapons delivery capability. Pilots interfaced with this pod through the MFDs and the hands-on controls on the side stick controller and throttle grip.

The specific objectives of this test were categorized into four main areas of concern. The first was to assess operability and controllability of the F-16/LANTIRN System integration mechanization, insuring that the controls and displays permitted proper operation, efficient and effective control, and provided sufficient feedback to the operator/pilot. The second was to assess pilot workload, verifying that the pilot could accomplish all navigation, TF, threat response, target acquisition, and weapons delivery tasks without undue workload.

The major thrust of this phase of Development Test and Evaluation (DT&E) testing for LANTIRN was to assess the overall impact of the TGP to the LANTIRN mission. The third objective was to assess the overall contribution of the LANTIRN TGP to the low level navigation task. (The TGP was not specifically designed to provide low level navigation capabilities. That was the intent of the NVP. The TGP was expected, nonetheless, to enhance low level navigation, and the extent to which it did was the intent of the third objective.) The fourth area of concern was to verify that the LANTIRN Fire Control System (FCS) and F-16 test aircraft were adequately integrated to provide the pilot a day or night, under-the-weather capability to detect and recognize targets, permitting successful weapons deliveries on the first pass at the target. It was determined during the planning phase of testing that, to a large degree, all these objectives could be achieved within a comprehensive workload evaluation that employed the various aircraft subsystems associated with the F-16/LANTIRN mission.

The objectives were satisfied with a flight test program that consisted of 56 nighttime, low level sorties conducted in a simulated operational environment (unfamiliar terrain, unfamiliar targets, etc.) under simulated operational conditions (mission planning folders, simulated attacks, etc.). Due to the complexity of the avionics suite which comprised the F-16/LANTIRN System, the task of flying these sorties under these conditions was difficult and often hazardous. As a result, the test methodology that was used successfully to satisfy these objectives had to be, and was, as unobtrusive as possible.

OVERALL TEST METHODOLOGY

The testing was conducted and data were collected during three distinct phases; training, Systems Integration (SI), and specialized demonstrations. The test method employed during the training phase was very similar to what was used in the SI phase. The bulk of this testing centered on the SI phase, therefore, our discussion will concentrate on this phase of testing. In general, the demonstrations were based upon another set of objectives and have been excluded from the remainder of this discussion, with the exception of one demonstration. This demonstration was the verification of F-16/LANTIRN System single-seat effectiveness. This was a special phase of testing wherein the pilots did, in fact, fly the F-16/LANTIRN mission single seat. This demonstration followed the SI phase and, in terms of the assessment of systems integration and pilot workload, was conducted exactly like the preceeding SI phase. Therefore, once again, the bulk of this treatise will be a discussion of the method used during the SI phase.

Five experienced test pilots participated in the data collection aspects of the training and SI phase of testing as well as the single-seat effectiveness demonstration. They were from a variety of backgrounds and their actual flight time in an F-16C/D aircraft varied from 86 to 380 hours. The following table presents the test subjects' overall flight experience.

LANTIRN PILOT FLIGHT EXPERIENCE

	F-16C/D Hours	Total F-16 Hours	Total FTR/TNR Hours	Total Hours	Other Aircraft Flown
Pilot A (AFOTEC)	86	1162.1	1648.4	2760.7	F-4, T-38
Pilot B (TAC)	380	956.5	1895.4	2164.1	F-4, T-38
Pilot C (AFSC)	359	1497.7	4408.7	4986.2	F-4, RF-4, T-33, T-38, F-102, F-104
Pilot D (AFSC)	371	469.3	2634.7	3024.1	F-4, F-15, T-38
Pilot E (AFSC)	170	782.4	2077.5	2346.1	F-4, AT-38B

NOTE: Fighter/Training (FTR/TNR), Air Force Operational Test and Evaluation Command (AFOTEC), Tactical Air Command (TAC), and Air Force Systems Command (AFSC).

The training phase consisted of sorties which were conducted to increase pilot proficiency with the system as well as to facilitate pilot familiarity with the data collection procedures prior to the SI phase. As mentioned previously, the SI phase was the most critical phase in terms of data collection. However, the training phase was crucial to the overall successful collection of subjective data during the SI phase as it provided the invaluable opportunity to train pilots as psychophysical observers. The training sorties were a combination of low level navigation and weapons delivery maneuvers exercising all NVP and TGP functions to be tested during the SI phase. These sorties were flown in the Edwards AFB complex, with attacks on familiar targets, so that emphasis could be placed on achieving proficiency with the F-16/LANTIRN System as well as with the subjective test method.

The SI phase consisted of six different mission scenarios that were flown low level at night, terminating in one of three different types of simulated weapons deliveries, with three attacks per scenario. These scenarios were initially flown in two-place F-16B aircraft with two LANTIRN-qualified pilots. The rear cockpit pilot functioned as a safety pilot and was familiar with the route flown and the targets being attacked. In general, the rear cockpit pilot was not permitted to prompt the front seat pilot unless a safety of flight event were to occur. He did, on occasion, assist the front seat pilot with the subjective portion of the test.

The front seat pilot saw both the actual route and targets for the first time during SI. One of the constraints of this test was that these simulated operational mission scenarios would have to be flown, to a large extent, over terrain and against targets that might be familiar to the pilots. However, the particular routes, comprised of specific low level navigation legs with specified target assignments and target headings, were new to the pilots. Planning for each mission was confined to the day of the sortie (all sorties were flown at night). It began several hours before "step time" when the pilot received his "intelligence data" (which was a mission folder containing route information, weapons data, specific rules of engagement, pictures, infrared (IR) film clips, detail maps, etc.) giving him what was thought to be operationally representative, detailed information relative to the test sortie. After the mission was planned, it was flown and completely debriefed.

Performance Measurement

Simulated attack performance was evaluated immediately following an attack by the pilot. The parameters used to make the assessment had been defined prior to the start of the test and were specific to the type of weapons delivery. Accuracy of the real-time assessments was not always constant. On numerous occasions following the mission, during the video tape review, the initial assessments were revised to comply more exactly with the defined parameters.

SUBJECTIVE TEST METHODOLOGY

The operability and controllability evaluation was conducted primarily in conjunction with the training and SI phases. Two subjective forms were used to document pilot comments and opinions. To obtain pretest or baseline information, an operability and controllability form was administered to the pilots prior to SI testing. This form solicited their impressions of the integration of the two systems (LANTIRN and F-16) as they knew it from their training phase of flight, as well as from their flying during earlier developmental testing of the F-16/LANTIRN System. At the termination of the SI sorties, pilots completed the operability and controllability form again. The two sets of responses were compared and analyzed. This particular test procedure yielded information pertinent to all objectives associated with the test effort. Results from these forms indicated specific areas where there were still significant mechanization issues which needed to be addressed within the existing deficiency reporting system.

The workload evaluation was accomplished during the SI phase. There exists a plethora of definitions on workload in the literature. However, it appears that most of these definitions can be placed into one of three broad conceptual groups: those related to the demands of the flight tasks--input load, those associated with the response to those demands--operator effort, and interpretations of workload based on work results or performance (Reference 1). For this test, workload was viewed as a multidimensional construct which was a mixture of each of these interrelated conceptual groups.

It was well known from earlier developmental testing, as well as from the training phase, that the complexity of the F-16/LANTIRN System had elevated the pilot's role primarily to that of a systems manager, wherein the pilot must allocate his workload to monitor four displays, evaluate threats, terrain follow and terrain avoid, select weapons, employ electronic countermeasures (ECM), etc., and fly the aircraft. This task complexity suggested that perhaps the most important criterion for selecting a metric for this test would be intrusiveness. This fact, along with the basic complexity of the workload concept, suggested a global indicator of workload (i.e., subjective indication of overall workload) would be the most appropriate analysis technique. One global workload assessment technique that is capable of satisfying all selection criteria requirements (i.e., sensitivity, diagnosticity, intrusiveness, validity), plus possess universal acceptability, does not exist. We decided that a comprehensive approach to workload assessment would result if two subjective techniques were employed. Both metrics would be supported and validated to a large extent by the structured interviews and ancillary subjective narrative to be elicited from the pilots. The plan was to develop a modified Cooper-Harper-type scale specifically for F-16/LANTIRN SI testing applications. This scale would be used in conjunction with a subjective procedure known as Subjective Workload Assessment Technique (SWAT).

The workload scale developed for LANTIRN SI was patterned after the well-known Cooper-Harper handling qualities rating scale (Reference 2). The Cooper-Harper Scale (CHS) has been used so extensively for assessing handling qualities that it has become a standard in the flight test community. The CHS is a global rating technique that combines a binary decision tree with a 10-point scale. In spite of the fact one half of the words on the CHS are workload related, research indicated that the scale is best suited (i.e., more sensitive) to tasks that are predominately motor or psychomotor in nature (Reference 3). This was by design because the CHS was originally conceived to assess pilot motor or psychomotor activities required in the piloting of an aircraft. However, with an integrated aircraft/avionics system as complex as F-16/LANTIRN, pilots rely on cognitive abilities (perception, communication, monitoring, evaluation, problem solving, etc.) to a greater extent than on motor or psychomotor skills.

The original CHS has been modified by many experimenters (Reference 3). In these instances, the modifications to the original CHS did not incorporate a major change to the overall emphasis. However, beginning in 1981 and continuing through 1983, the researchers, Casali and Wierwille, with the intent of creating a scale that could be used specifically for assessing workload, developed and tested a modified version of the original CHS that stressed the more cognitive aspects of task accomplishment (Reference 3).

The studies performed by Casali and Wierwille demonstrated that certain modifications could be made to the original CHS with the modified scale retaining the sensitivity, reliability and validity of the original scale. The modifications involved the wording within the scale, aligning it with the cognitive aspects of workload. As a result of their research, they produced a statistically reliable scale that could be used as an overall indicator of mental workload. They called their scale a Modified Cooper-Harper Scale (MCH) (Figure 1).

A scale similar to the CHS or the Casali and Wierwille MCH was determined to be the most appropriate choice for one of two subjective opinion measures for SI testing for a variety of reasons. One justification was that the test pilot community is very familiar with the original CHS. It is well known that people tend to ascribe legitimacy to techniques that are familiar to them. As a result, a priori acceptance of a scale that resembled the original Cooper-Harper was expected and received. Test subject acceptance of test methods is one of the most important elements in subjective evaluations.

The Casali and Wierwille MCH scale was not considered appropriate for direct application to SI testing without modifications. Their MCH scale did not incorporate performance criteria associated with various levels of workload. We needed a measure that integrated perceived workload and perceived performance. We assumed that minor modifications to their MCH scale could be made without significantly altering the validity of the scale. The format, and in particular, the inclusion of a binary decision tree, were thought to be the most important attributes that should be retained in the development of a LANTIRN workload/performance assessment MCH scale.

Our goal was to design a scale that (1) closely resembled the format of the original CHS as well as the Casali and Wierwille MCH scale, (2) integrated perceived workload associated with perceived attack performance,(3) involved some measure of F-16/LANTIRN System integration, and (4) was succinctly worded to fit on a standard 5-inch by 8-inch flight card.

The LANTIRN-specific MCH scale that was finally developed was called the LANTIRN Workload Scale (LAWS) (Figure 2). The attack performance descriptors, "DES" for DESIRED, "ADQ" for ADEQUATE, and "INADQ" for INADEQUATE, were defined by performance parameters relevant to three different weapons delivery categories. Although somewhat artificial, as they were not exactly representative of the maneuvering tactics that might have been employed in a true operational scenario, the parameters did, nonetheless, provide general guidelines for standardizing pilot performance. This permitted comparisons between individual pilot performances specific to the three types of deliveries.

For this test, perceived workload was divided into three major categories to indicate increasing levels of workload. Each workload category descriptor (minimum, moderate, and extensive) was associated with a respective F-16/LANTIRN System characteristic, attack performance rating (as above), and LAWS numerical rating. For example, the "minimum" workload descriptor was associated on the scale with F-16/LANTIRN System characteristics like "good--negligible deficiencies" and "DESIRED" attack performance, with a numerical rating of 2; or "minor but annoying deficiencies" and "ADEQUATE" attack performance, with a numerical rating of 4. The LAWS was divided into three groups of three, with a separate group for major deficiencies where improvement was mandatory (numerical rating of 10).

The SWAT procedure referred to earlier and incorporated into this test as the second subjective opinion measure, was developed by the Air Force Aerospace Medical Research Laboratory (AFAMRL). For background development information on SWAT see Reference 4. SWAT defines relative perceived workload in three dimensions: (1) time load, (2) mental effort load, and (3) psychological stress load. The following descriptions of each dimension developed by AFAMRL were given to the test subjects:

Time Load

Time load refers to the fraction of the total time that you are busy. When time load is low, sufficient time is available to complete all of your mental work with some time to spare. As time load increases, spare time drops out and some aspects of performance overlap and interrupt one another. This overlap and interruption can come from performing more than one task or from different aspects of performing the same task. At higher levels of time load, several aspects of performance often occur simultaneously; you are busy, and interruptions are very frequent.

Mental Effort Load

As described above, time load refers to the amount of time one has available to perform a task or tasks. In contrast, mental effort load is an index of the amount of attention or mental effort required by a task regardless of the number of tasks to be performed or any time limitations. When mental effort load is low, the concentration and attention required by a task is minimal, and performance is nearly automatic. As the demand for mental effort increases, due to task complexity or the amount of information which must be dealt with in order to perform adequately, the degree of concentration and attention required increases. High mental effort load demands total attention or concentration due to task complexity or the amount of information that must be processed.

Psychological Stress Load

Stress load refers to the contribution to total workload of any conditions that produce anxiety, frustration, or confusion while performing a task or tasks. At low levels of stress, one feels relatively relaxed. As stress increases, confusion, anxiety, or frustration increase and greater concentration and determination are required to maintain control of the situation.

According to the SWAT procedure, each of these three dimensions was assigned three levels, corresponding roughly to high, medium and low loading. A precise definition for each level, as developed by AFAMRL is shown in Figure 3. The SWAT procedure started by having the test subjects perform what is called a "card sort". The card deck consisted of 27 cards with all possible combinations of the three levels of the three dimensions of workload. The test subjects rank ordered the workload descriptors according to their personal perceptions of workload. The individual card sorts from the test subjects were combined through a mathematical procedure known as conjoint measurement. Conjoint measurement tests the ordered data to determine the combination rules used by the subjects. An additive model leads to a combined workload score, incorporating time load, mental effort, and psychological stress, on an interval scale ranging from zero to 100.

The SWAT card sort information obtained from each test subject was analyzed with the AFAMRL SWAT computer program. This program determined prototypes for the individual subjects. For example, a subject that was a "time" prototype considered the time load dimension to contribute the heaviest to his perception of workload. There were six possible prototype groups. The two highest correlation coefficients of the six determine to which group the subject belongs. Of the five test subjects who participated in SI testing, three were prototyped "stress", with "time" the second factor; and two were prototyped "time", with "stress" the second factor.

Group scaling was also provided by the SWAT computer program. For group scaling, the data from all subjects was averaged together and conjoint analysis derived a single scale for the group. To use group scaling, the derived Kendall's Coefficient of Concordance had to be greater than 0.78. The SI test subjects had a Kendall's Coefficient of Concordance of 0.897 which indicated a high level of agreement among test subjects. If the coefficient had been lower than 0.78, either prototype or individual scaling would have been used for the scaling in this test.

The combined values were broken down at the end of the SI testing phase into five categories representing various levels of workload (Table 1).

Table 1

SWAT DESCRIPTIVE LEVELS OF WORKLOAD

SWAT SCORE	WORKLOAD LEVEL
0.00 - 15.99	Minimum
16.00 - 29.99	Moderately Low
30.00 - 55.99	Moderate
56.00 - 69.99	Moderately High
70.00 - 100.00	Extensive

The combined SWAT scores were not normally distributed. By selecting the categories shown in Table 1, an approximate normal distribution of the data set was achieved. The lack of normality for the combined SWAT data was probably an effect of sample size or selection.

The two subjective metrics employed during this test were LAWS and SWAT. Immediately following an attack, the test subject/pilot rated the attack sequence using these two metrics. Therefore, pilot workload was evaluated per attack sequence, including ingress and egress. In addition, to gain some workload information relative to the low level portions of the flight, the subjects rated these segments using the SWAT technique. As LAWS was attack specific, it was not used to evaluate the low level navigation portions of the test.

The six routes used during the SI phase were designed to test the navigation capability of the F-16/LANTIRN System over various types of terrain and targeting/attack capability against targets of several thermal contrasts. Terrain varied from the flat, dry lakes of the Mojave Desert to the rolling hills of the central California coast and rugged mountains of the Sierra Nevada. Weather conditions also varied from the clear, low humidity conditions found in the desert, to low overcast, high humidity conditions found along the central California coast.

Each profile required that the pilot navigate past three turnpoints prior to reaching a simulated target. Three targets were included on all routes. Although in a true operational scenario there is generally no more than one target/attack sequence per route, we included three separate target/attack combinations to maximize data acquisition. More than three targets would have drained the pilots' mental and physical reserves and would have confounded the test results, in particular the workload results.

Pilots were asked to evaluate the F-16/LANTIRN System performance and its contribution to pilot workload for each attack sequence using the LAWS and SWAT. To facilitate data collection, most routes were designed with an orbit following the attacks. The orbit gave the pilots an opportunity to pop up out of the low altitude environment so that they could provide the necessary workload information without impacting the workload associated

with setting up for the next turnpoint or attack. In addition to rating the attacks, pilots were requested to comment as often as they could "real time" (their comments were recorded by the onboard video recording system) on the operability and controllability of the LANTIRN system, and on F-16/LANTIRN System capabilities, deficiencies, and workload.

A flight card containing the abbreviated LAWS narrative and a SWAT mnemonic was designed to allow quick interpretation and use by the pilots in the flight environment. Approximately 10 variations of a flight card were flight tested during the training phase of SI. Finally, an acceptable flight card was created that contained the most salient workload related words with associated attack performance and SWAT information (Figure 4). To rate the attacks, pilots would "step" through the flight card beginning with the boxed question in the upper left-hand corner. For the SWAT score the pilots could use the SWAT mnemonic provided, or, if they preferred, the rear cockpit safety pilot could read them the full SWAT descriptors that were listed on the reverse of the flight card (Figure 3).

The pilots were very conscientious about giving accurate scores using both metrics. With very few exceptions, they were able to "walk through" the binary decision tree associated with the LAWS and arrive at a LAWS rating that unambiguously reflected the perceived workload required to achieve a certain attack performance. To a large extent the acceptance of the method was a result of their total familiarity with the procedures and the subjective metrics that they were exposed to during the training phase of testing.

On a couple of occasions, a situation occurred wherein the pilot would report a performance rating of "INADEQUATE" which he attributed primarily to pilot error. The error was in attacking the wrong target. There were no LANTIRN System malfunctions, aircraft integration problems, or workload issues. Often, during the extensive postflight video tape review, the error could be shown to be attributable to excessive workload before the target acquisition phase, to the less than optimum (small) display size for TGP FLIR, to INS drift, or to a deficiency in mission planning by the pilot. The LAWS did not provide for these anomalies. This type of situation occurred very infrequently. Consequently, it was decided this anomaly did not invalidate the general use of the LAWS. In addition, these anomalies had little effect on the overall workload test results.

Subsequent to each flight a debriefing was held to evaluate the overall effectiveness of the mission. A review of the recorded video, with particular emphasis on the attack sequences, occurred afterwards. During these sessions, test subject/pilots participated in a structured interview.

At the completion of all testing, overall mission effectiveness was defined as the total of all DESIRED and ADEQUATE attack performances.

DISCUSSION

As a result of using the two subjective metrics, supplemented by pilot narrative, a global view of F-16/LANTIRN System integration and workload was achieved. In addition, we were able, as a function of the LAWS metric, to compare and contrast attack performance for the three types of weapons deliveries and derive an overall effectiveness rate. All actual test results were classified. Therefore, the "results" contained within this section are listed generically and may only be interpreted as general representations of the data we received as a result of this test methodology.

A summary of workload ratings for the three weapons delivery types was derived from the LAWS metric (Table 2) and from the SWAT (Table 3).

TABLE 2

LANTIRN WORKLOAD SCALE (LAWS) SUMMARY FOR SYSTEMS INTEGRATION WEAPONS DELIVERY TYPES

Weapons Delivery Types	Numbers of LAWS Ratings		
	Minimum	Moderate	Extensive
A	11	9	5
B	3	17	9
C	9	19	2
TOTAL	23	45	16

NOTE: The totals for each weapons delivery type, across LAWS and SWAT ratings, do vary. Some test sorties were deemed ineffective due to extenuating circumstances, like weather or aircraft subsystem failures.

TABLE 3

SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE (SWAT) SUMMARY FOR SYSTEMS INTEGRATION WEAPONS DELIVERY TYPES

Weapons Delivery Types	Numbers of SWAT Ratings				
	Minimum	Mod Low	Moderate	Mod High	Extensive
A	5	7	8	2	3
B	5	4	6	3	11
C	10	2	8	4	6
TOTAL	20	13	22	9	20

The data in Table 2 suggested a global workload assessment of "moderate" for these three weapons delivery types. This statement was corroborated by the SWAT results presented in Table 3. However, note the number of "extensive" responses on both tables. In all cases (Tables 2 and 3), these "extensive" ratings suggested the occurrence or near occurrence of "overload" situations. "Overload" situations are those subjective experiences in which the entire complement of elements that comprise workload for any given event results, generally, in degradation of performance. Overload may occur at different levels for different individuals. "Extensive" ratings also suggested that little workload reserve capacity existed for other unplanned elements of a complex task.

As mentioned earlier, both metrics were compared to a large volume of narrative information obtained from the pilots both during and after flight. The primary reason for measuring workload was to identify conditions under which attack performance could be expected to deteriorate. As a result of this methodology, we were able to determine and report on the extenuating factors that either did, or could realistically be expected to, contribute to the "extensive" ratings and subsequently impact overall workload and performance. The factors thus identified varied tremendously between what could be controlled (e.g., mission planning, known deficiencies or limitations of the test, tactics) and those factors which could not be controlled (e.g., a shift in pilot priorities, humidity, weather, target characteristics that were less than optimum, system anomalies that interfered with or caused the pilots to have to compensate in order to execute the attack precisely, etc.). In addition, two other factors that may have impacted workload and performance were not controlled in this test: work durations and proficiency levels.

When we isolated the three possible workload categories from the LAWS scores (minimum, moderate, and extensive) and plotted them with the SWAT combined workload ratings, the data showed a positive relationship between the two workload techniques. When we plotted LAWS combined workload and performance scores (numbers 1 through 10) with the SWAT combined workload ratings, the data tended to show a positive correlation and were somewhat homoscedastic (Figure 5). This correlation is not conclusive.

In general, despite the extensive training, and to a certain extent, terrain and target familiarity, the workload responses, from both techniques, were distributed throughout the range of workload possibilities, across weapons delivery types, and were not always dependent upon level of performance. This was probably due to the same combination of effects or extenuating factors, as mentioned above.

For the low level navigation assessments, we relied primarily on subjective narrative elicited by structured interviews. This procedure revealed that, in general, the TGP served to increase overall pilot situational awareness. In addition, the pilots evaluated a limited number of specific navigational segments using SWAT. These results yielded important relative workload information and enabled us to make definitive statements regarding the overall contribution of the Targeting Pod to the low level navigation portion of the F-16/LANTIRN mission.

CONCLUSION

The general conclusion from this effort was that it was impossible to predict potential workload from observing performance. This is consistent with other reports (Reference 5). However, due to the test methodology just described, it was possible to identify those factors which degraded performance, or forced the requirement for excessive pilot compensation with a concomitant increase in pilot workload.

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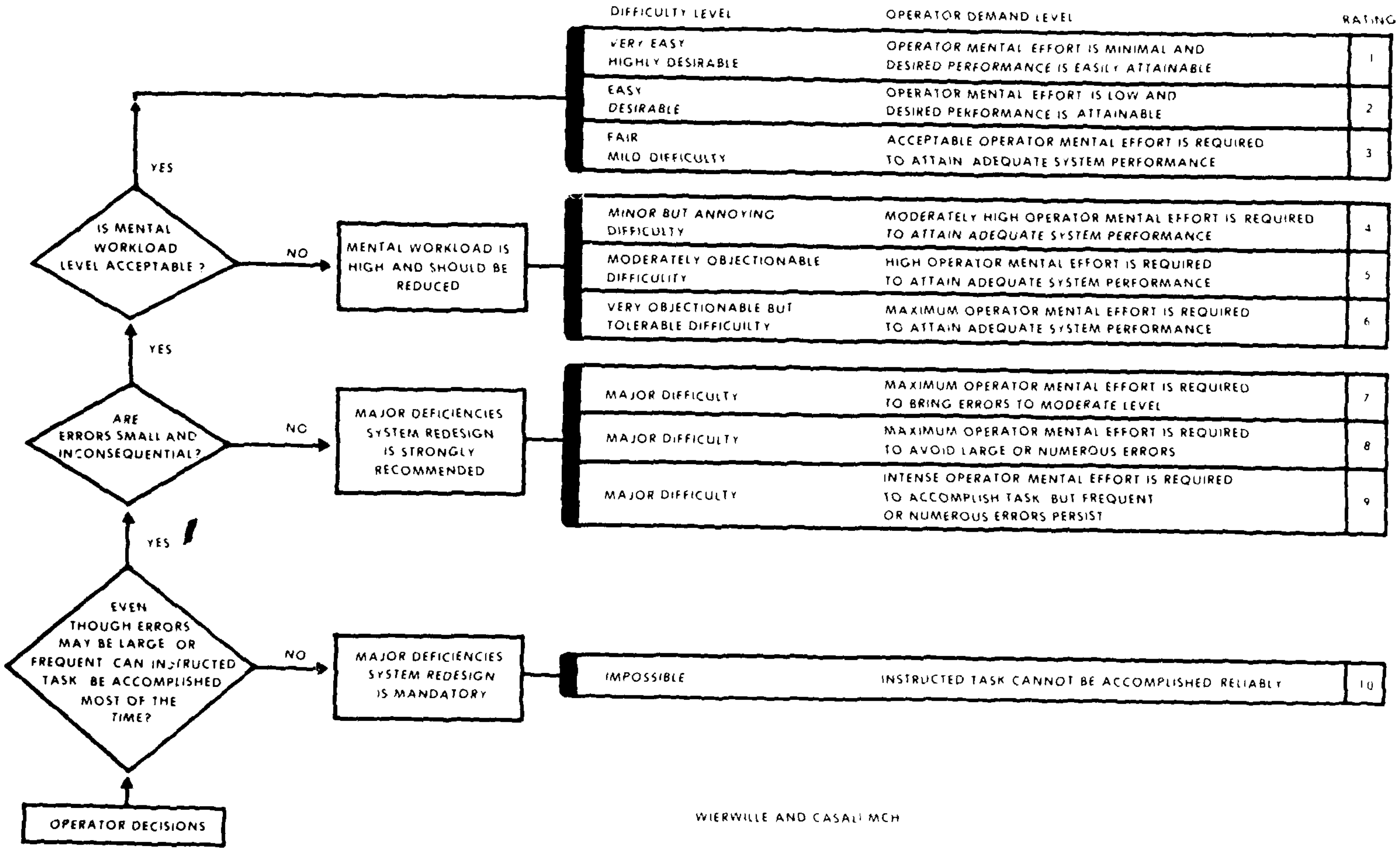

WIERWILLE AND CASALI MCH

LANTIRN WORKLOAD SCALE

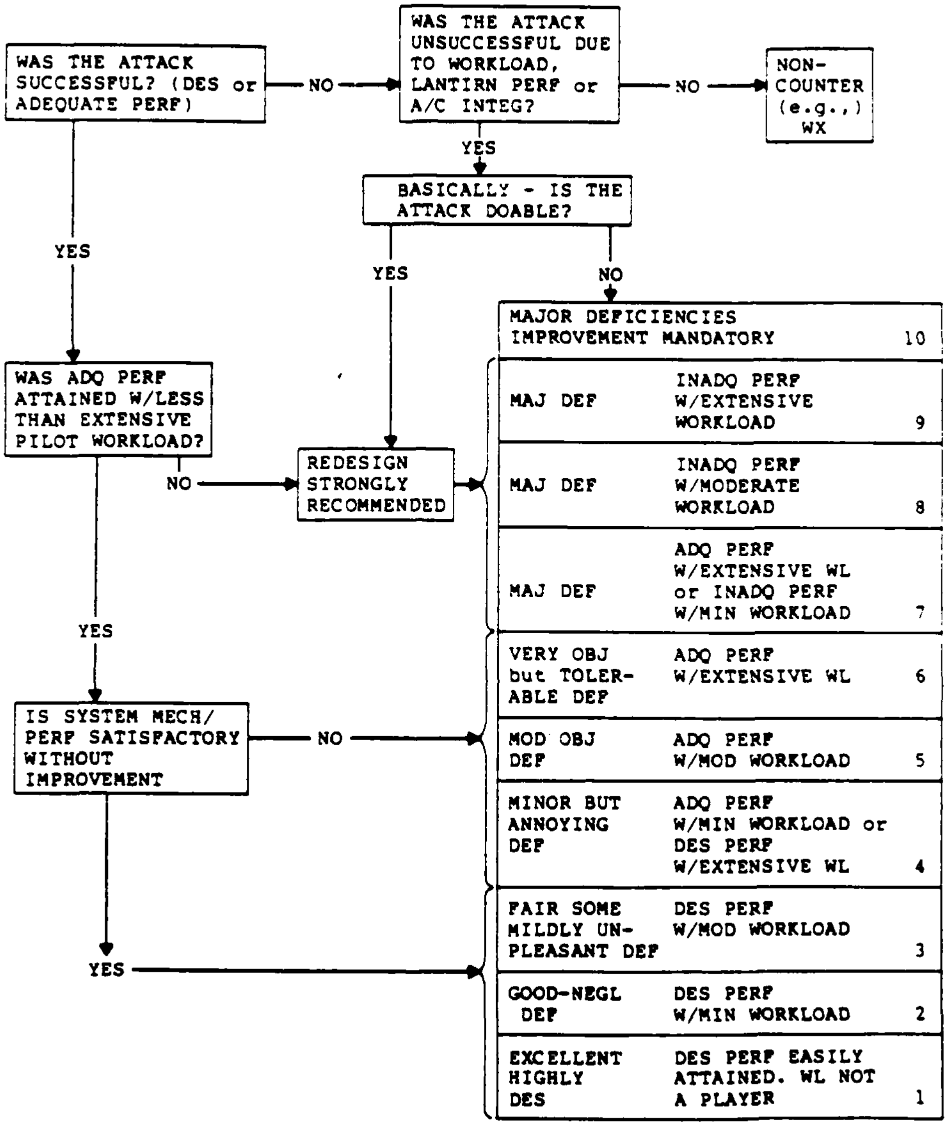

Figure 2

SWAT - FULL NARRATIVE

I. TIME LOAD

1 Often have spare time. Interruptions or overlap among activities occur infrequently or not at all.

2 Occasionally have spare time. Interruptions or overlap among activities occur frequently.

3 Almost never have spare time. Interruptions or overlap among activities are very frequent or occur all the time.

II. MENTAL EFFORT

1 Very little conscious mental effort or concentration required. Activity is almost automatic requiring little or no attention.

2 Moderate conscious mental effort or concentration required. Complexity of activity is moderately high due to uncertainty, unpredictability or unfamiliarity. Considerable attention required.

3 Extensive mental effort and concentration are necessary. Very complex activity requiring total attention.

III. PSYCHOLOGICAL STRESS

1 Little confusion, frustration or anxiety exists and can be easily accommodated.

2 Moderate stress due to confusion, frustration or anxiety. Noticeably adds to workload. Significant compensation is required to maintain adequate performance.

3 High to very intense stress due to confusion, frustration or anxiety. High to extreme determination and self-control required.

FIGURE 3

SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE (SWAT)

SWAT (FULL NARRATIVE ON BACK)

TIME		MENTAL EFFORT		STRESS	
SPARE	1	VERY LITTLE	1	LITTLE	1
SOME SPARE	2	MODERATE	2	MODERATE	2
NO SPARE	3	EXTENSIVE	3	INTENSE	3

LANTIRN WORKLOAD SCALE

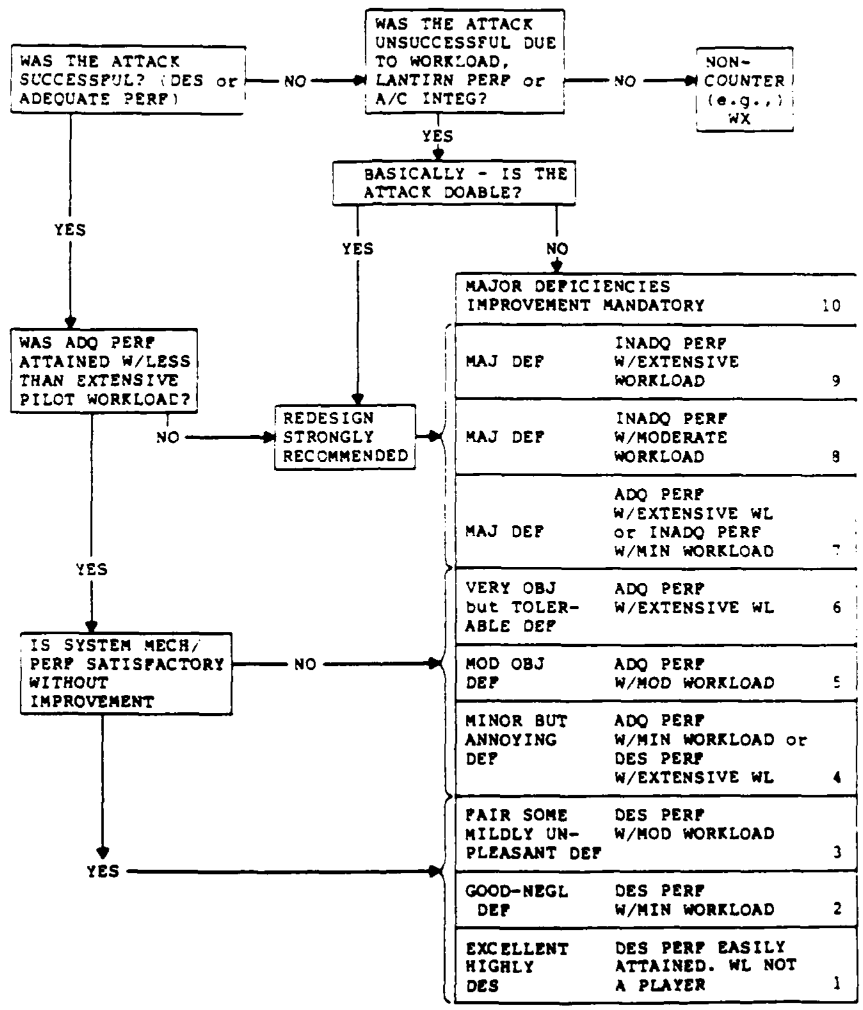

FIGURE 4

SWAT/LAWS FLIGHT CARD

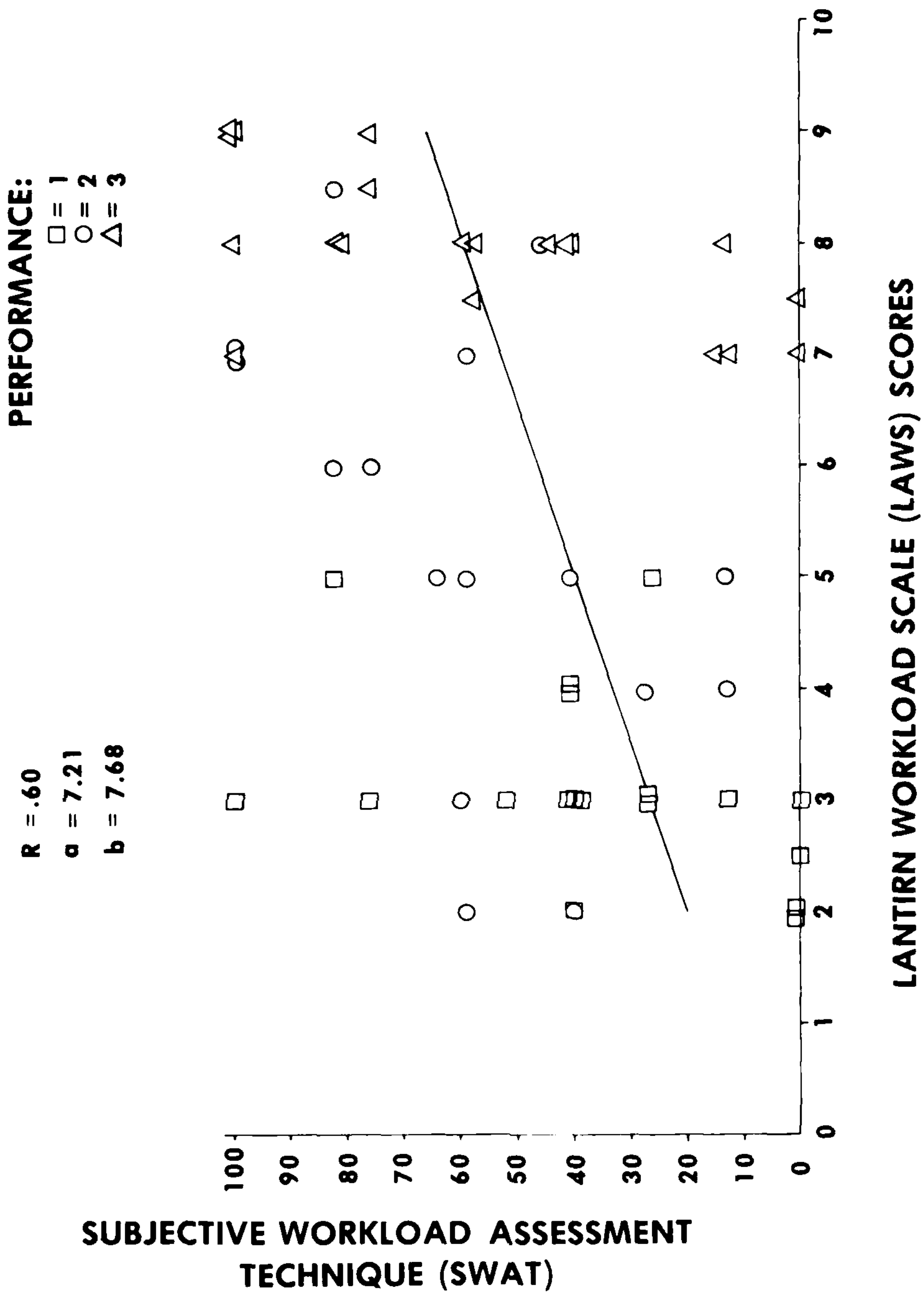
PERFORMANCE:
□ = 1
○ = 2
△ = 3
R = .60
a = 7.21
b = 7.68
LANTIRN WORKLOAD SCALE (LAWS) SCORES
SUBJECTIVE WORKLOAD ASSESSMENT TECHNIQUE (SWAT)

FIGURE 5

CONSIDERATIONS CONCERNING THE ASSESSMENT OF PILOT WORKLOAD FOR COMPLEX TASK CONDITIONS

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SUMMARY

Workload research has led in the past to the development of various measures, mostly concerning different aspects of task workload, in a separate and isolated way. In addition, present opinion assumes more and more that, in order to achieve a satisfactory workload evaluation, a matrix of measures is needed.
This paper discusses a number of considerations concerning the problem of being able to draw conclusions from a variety (i.e. a matrix) of experimental measures in a complex task situation. Several implications are pointed out, such as the problem of dealing with contradictory outcomes, the designating of artefacts, and the problem of formulating final concuisions without the (a-priori) availability of a superior method for evaluating other methods.
These considerations have been examined in detail in an in-flight study concerning the assessment of pilot workload under various instrument approach conditions for a fixed-wing (civil) transport aircraft. The experimental findings have been compared with the results of a former in-flight experiment dealing with pilot workload and performance during helicopter (instrument-flying) tasks.
A discussion is given of the results consisting of subjective ratings, physiological measures, and task performance measures. A strategy is discussed, dealing with the formulation of final conclusions based on the outcomes of a matrix of measures.

ABBREVIATIONS

ABP	Average band power
AGL	Above ground level
AP	Autopilot
ATPL	Airline transport pilot licence
b.p.m.	Beats per minute
CPL	Commercial pilot licence
dB	Decibel
DME	Distance measuring equipment
e	Error (or: residual) variation
FD	Flight director
G	Groningen airport
IF	Instrument-flying
ILS	Instrument landing system
KT	Knot(s)
M	Mean
NDB	Non directional beacon
NLR	National Aerospace Laboratory
P	Pilot
R	Rotterdam airport
RMS	Root mean square
RMSSD	Root mean square of successive differences
SD	Standard deviation
SYNC	Synchronizer
T/L	Take-off and landing
VHF	Very high frequency
VOR	VHF omnidirectional range
VTHR	Threshold speed
WL	Workload

INTRODUCTION

During the last two decades considerable research efforts have been devoted to developing a proper framework from which pilot workload can be analysed in a systematic manner. In this context, several attempts have been made to come to an unequivocal definition of the concept "workload" as well as to find an adequate method for its "measurement". At present it must be stated, however, that these efforts have not yet produced a satisfactory result. Although there is general agreement among investigators about the existence of different measures which could be used in some way as workload indicators, there is still no agreement about which these are, about which are the most effective, or about how (combinations of) these measures can be related to changes in the workload of an operator.

This situation has resulted in the development of a large number of measures for "quantifying" the operator's workload, whereas relatively little systematic research has been devoted to basic aspects, such as estimating the sensitivities of specific measures with respect to different task conditions and the relative practical usefulness of different techniques within different operational environments. Furthermore, it has been assumed in a growing number of workload investigations that we are dealing with a multidimensional concept, hence a combination of measures is needed, or alternatively one measure with sensitivity to several dimensions, in order to come to a satisfactory evaluation of the operator's workload. This idea has had little impact, however, on the development and use of workload measurement techniques.

The foregoing outlines some reasons for developing a new approach towards the study of workload measurement. Such an approach should be based upon the presumption that the concept of workload encompasses various task- and operator-related aspects, for which each measure will most likely have a different sensitivity. In addition, the data obtained with these different measures must be integrated in a proper way in order to arrive at valid conclusions.

In the following, the implications of such an approach are discussed in detail . The resulting consequences are judged on their merits on the basis of the outcomes of two in-flight workload studies. The first study deals with instrument approaches carried out on a (civil) fixed wing aircraft under a variety of approach conditions. The second study concerns helicopter instrument-flying tasks, such as hovering and tracking.

The considered workload measures include subjective ratings, physiological measures, control activity measures, and (mathematical) model measures. The pertinent outcomes are discussed in connection with a strategy to arrive at an overall conclusion on the basis of the individual results of different measures.

BASIC IDEAS AND AIMS

The basic ideas and aims behind this study, can be formulated more specifically as follows:

(1) It is assumed that workload generally encompasses several components, such as time stress, effort, etc. It is not clear which components play a part in a specific situation, nor what the impact is of each upon the overall perception workload. It is therefore advocated that attention be paid to the sensitivity of specific workload measures to different aspects of the task.

(2) As a further consequence of (1) it can be stated that research on workload measures should not be based upon any underlying assumptions about the existence of a superior method which can be used as a criterion (e.g. "task complexity") for the evaluation of other methods. Any such a-priori selection of task conditions according to a particular criterion, which may emphasize specific properties of a given task situation, could conceivably suppress the usefulness of certain other measures, due to an insufficient degree of variation of other task variables to which these measures are specifically sensitive. In other words, any assumption which supposes that "degrees" of workload can be indicated on the basis of one criterion exclusively, is contradictory to the idea that workload is multidimensional. Investigations of workload measures should therefore not start from an a-priori ranking of task conditions with respect to the expected "amount" of workload involved in the tasks. Instead, the underlying rationale for drawing certain conclusions should first be considered carefully .

(3) Most workload studies focus exclusively on identifying differences in workload. It is important, however, that such studies focus also on the problem of indentifying similar workload levels with respect to different tasks. This can have considerable consequences for the experimental design. Equivalence in workload level has, for example, still not been demonstrated in cases where measured differences do not reach a significant level. It is necessary in workload studies, therefore, to establish the power of the intended statistical tests in an early stage of the investigation. Only in cases of sufficient power of the statistical tests being used (larger than, say, 0.7) it is possible to identify - with a reasonable certainty - both possible similarities and differences in workload for different task situations.

(4) As a consequence of (3), minimal differences of interest ("indifference margins") have to be specified with respect to each workload measure. The smaller these minimal differences are, the larger the sample-size must be in order to obtain the same power of the test. It is usually of little interest, for example, to detect "small" differences between two tasks, such as differences in average heart rate of, say, 0.1 beat per minute, or differences on a 10-point rating (interval-) scale between values of, say, 6.2 and 6.3.
By carefully selecting plausible indifference margins, it should therefore be possible to use workload measures as indicators of differences as well as of similarities in workload at an a-priori specified power. Clearly, there is a need for a general agreement in connection with the specification of the indifference margins for workload measures.

(5) Once the data from a specific measure have indicated that either a (positive or negative) change or an equivalence in workload has occurred, it is necessary to define a strategy for drawing conclusions on the basis of a number of different modality measures, including some possibly contradictory results. Such a strategy should preferably be uncomplicated in its utilization so that the final (overall) conclusions will not give rise to problems of interpretation. An obvious strategy would be based upon the degree of homogeneity in the results. The desired level of homogeneity must be stated by convention. That is to say, when using several measures simultaneously, it should be acceptable to tolerate a certain percentage of diverging results when formulating the final conclusion. Alternatively, all deviating outcomes must be inspected on the presence of, for instance, artefacts which could raise the cost of an investigation considerably. If a critical amount of deviating results is exceeded it is necessary to carry out additional investigations of the considered cases until the desired level of homogeneity in the results has been obtained.

(6) The task situations to be selected for workload experiments must correspond to the ultimate complex operational environment for which the methods are intended to be used. This objective also supports the need for in-flight research programs, to be used as a common basis for different investigators for comparing and collating measures, evaluating strategies, effects of task aspects, etc. Such programs can be extended by including progressively more relevant task situations, ultimately arriving at a general framework from which operationally oriented pilot workload studies can proceed systematically .

(7) The development of any workload assessment method should have the objective that the ultimate application of the method must not rely on the availability of an extensively equipped research aircraft for the necessary data recording. Neither should the data analysis and the interpretation of the outcomes require the knowlegde of an expert. Otherwise, workload research will possibly never surpass the laboratory environment.

IN-FLIGHT EXPERIMENTS.

The foregoing considerations have led to the development of an in-flight experimental program by which the feasibility of such an approach can be inv stigated. The program deals with various instrument approach conditions for a fixed wing transport aircraft. Besides, the outcomes of a former, in-flight workload study concerning helicopter instrument-flying tasks are used as an additional basis to investigate the validity of the obtained results. Both experiments will subsequently be discussed in the following.

Fixed wing aircraft instrument approach experiment

Experimental Program

The experimental tasks in this experiment (Ref. 1) consisted of flying procedural approaches (with an external view occluding visor) with each experimental run starting on "downwind", approximately 10 minutes before touchdown. The independent task variables have been based on (i) the different approach aids, that is, ILS+FD, ILS, VOR+DME, NDB, (ii) the manner of pilot control, that is, automatic, manual, or manual with simulated trim malfuntion (i.e. retrimming prohibited after downwind), and (iii) the number of crew members, that is, 2 man versus 1 man crew. The experimental conditions are presented in table 1.

The approach pattern (for the ILS case) is illustrated in figure 1. All approaches consisted of four compatible segments: downwind, turn/intercept, 1st segment final (above 1000 feet), 2nd segment final (below 1000 feet), which are very suitable for making comparisons between scenarios on the basis of the workload data obtained. The approaches were terminated with an overshoot (at approximately 50 feet) to increase the flexibility of the program. (Note that some of the approaches must be flown in opposite direction to the rest of the landing traffic due to local circumstances of wind and beacon locations).
At a suitable moment before the overshoot (mostly just after passing the middle marker) the subject-pilot was reliefed from his IF-cap so that he could fly the last part visually.
Subjective ratings had to be given at the end of each segment (resulting in 4 ratings per approach). The ratings should concern the previously flown segment exclusively. Ratings were obtained from both the subject pilot and the safety pilot.

During the 2-man crew task conditions the safety pilot had to perform the duties of the first officier; i.e.: he should take care of ATC communication, select beacons, set flaps on request, read out checklists and perform such other activities as would be expected from the first officer. In the 1-man crew task conditions, the subject-pilot had to take over these duties in addition to the normal duties required for flying the aircraft.

The considered workload measures in the approach study are listed in Table 2. They cover a broad range of well-known workload assessment techniques. Besides, the selection of these measures have also partly been based on ground of considerations regarding the practical implications of their utilization in an operational environment.
The following discussions will be restricted to the most interesting results. For an extensive treatment of the separate results of all considered measures, the reader is referred to reference 1.

The experimental sessions have been carried out with the NLR Swearingen Metro II research aircraft (Fig. 2), which is a twin engine turboprop with a gross weight of 12,500 lbs. The relevant experimental parameters have been recorded by means of an aircraft related data acquisition system and an inertial reference system or are computed off-line from the recorded data (e.g. wind, thrust). The experimental data are partly grouped over the four segments (with exclusion of the rating parts at the end of each segment and the 'visual' part at the end of the fourth segment) and subsequently reduced to their relevant statistics. The data from some variables (among others, the flight path data) have also been stored on a time, and distance-to-go basis.

Each experimental session contained the 8 different approach conditions, which have been presented as much as possible in a random order. The sessions have been carried out at two airports (Rotterdam, Groningen), and were terminated, each time by means of a full stop (single or dual pilot) ILS approach at Schiphol airport; this time without requesting ratings from the subject pilot. By this, eventual effects due to the rating procedure, or the overshoot in stead of landing, could be traced (for the ILS type of approach).
The experimental program included in total 21 sessions, which have been carried out by 5 subject-pilots and 2 safety pilots (CPL and ATPL pilots).

Results

The experimental results have been based on analyses of variance upon the considered workload related data with respect to the 8 experimental conditions. Also analyses of covariance have been carried out to adjust for eventual effects of the uncontrollable conditions of gust, wind and (ATC) communication load. The important experimental results can be summarized as follows:

- First of all, a further selection among the workload measures had to be made (in addition to the aforementioned selection based upon considerations regarding their practical usefulness). This time the selection process was necessarily based upon aspects of sensitivity of the measures: a number of measures (e.g. heartrate variability and control activity measures) appear to lack sensitivity to task differences, due to large interaction effects between the factors subjects and tasks, or because of large intervening

environmental related effects (e.g. gustlevel). In addition to this, a number of measures is rather restricted with respect to their coverage; for instance, primary task performance measures reflect also inherent differences in the approach accuracy which can obviously related to the available approach aids in the pertinent conditions. Consequently, it becomes a complicated manner to adjust the pertinent data for these effects.

- Analyses of variance did not indicate any significant interaction effects between the experimental conditions (table 1) and the four approach segments (fig. 1). For all measures, except heartrate measures, the third segment results in the best discrimination among the experimental task conditions. Heart rate measures are the most discriminative in the fourth segment, possibly due to time-lag effects.

- The utilization of different measures tends to result - on the average - into similar workload patterns with respect to the different task conditions. Measures, which are to a less extent sensitive to different task conditions show more or less a fragmentary part of the aforementioned workload pattern. Figures 4 and 5 illustrate the workload patterns resulting from 2 measures of different modalities, namely subjective ratings (McDonnell's 10-point demand scale) and heart rate level. These figures show that both measures result in rather similar outcomes. Furthermore, the sensitivity of these measures to the different task conditions is concentrated within the last two segments.
The figures also show some specific aspects: for instance, the subjective ratings for the first segment reflect a difference in workload between the dual pilot NDB conditions with and without trim mal function, although the difference in trimmalfunction was not yet present during this approach segment. Note that this peculiarity did not occur in the average heart rate measure. On the other hand, the difference between single pilot and dual pilot conditions are for both measures more appearent during the first segment(s) than during the third segment, although the third segment involves the highest time pressure of all segments. Analysis of the video recordings for these conditions with respect to completion of the final checklist and the complying with ATC instructions showed a significant reduce in the accuracy of these cockpit activities during the single pilot cases (mainly due to failing to report compulsatory reporting points, and to complete the final checklist). This finding (for which the accuracy of the cockpit work can be regarded as a kind of "secondary task" performance) clearly indicates a higher workload level for the single pilot tasks in comparison with the corresponding dual pilot tasks (especially in the third approach segment).

The foregoing results, and also additional findings mentioned in reference 1, show that a matrix of measures is needed in order to arrive at reliable conclusions. Although different measures tend to result - on the average - in similar outcomes, each individual measure seem to have its specific weaknesses which can be compensated for by the additional use of other measures.

In the approach study also some attention has been devoted to examining the usefulness of mathematical pilot-aircraft system models for workload analysis. Two models have been considered, which are both based upon the optimal control model framework of the human operator. One of the models, the so-called control effort model (Ref. 6) reflects - in terms of the optimal control model framework - how hard the human controller has to work to achieve a given performance (criterion). It can be applied to manual control tasks, provided that an adequate aircraft system model is available and that the manual control task can be stated in model terms. The other model is an adapted version of the so-called Procru model (Ref. 5), and is capable, among others, of generating timelines for the relevant events during the execution of a ("raw" ILS) approach. Within the context of this investigation, the results of both methods are (because of the afore mentioned restrictions) compared with experimental data for a limited range of conditions (Ref.1) and are not used further for the purpose of the overall workload assessment of the different task conditions. Within the context of this paper it can be mentioned that the results from both methods agree fairly well with the corresponding experimental data. Besides, some findings with respect to control effort model parameter (E) will be discussed further in the following section in connection with the estimation of the so-called "indifference margins."

Overall assessment strategy

An important objective of the approach study concerns the investigation of an assessment strategy which satisfies the basic ideas and aims, as stated in the foregoing. One important issue concerns the power of the tests to be performed, in connection with the formulation of the mentioned "minimal differences of interest". The power of an analysis of variance depends, among other things, on the relative magnitude of an observed difference with respect to the standard deviation of the residual (i.e. error) variation, and also on the sample size. This is illustrated in figure 6 for the hypothetical case of an analysis of variance involving two experimental conditions. The figure shows that powerful assessments can already be obtained on the basis of a few observations, if the observed differences between the mean values (ΔM) of the pertinent variables are larger than circa 0.8 of the standard deviation of the residual random (error) variation (SD_e). Now, a safe strategy with respect to the choice of the magnitudes of the aforementioned indifference margins, would be, to let these margins (for each workload measure) be larger than the standard deviation of the remaining random variation (occurring in the data of the pertinent workload measure).

Figure 6 shows also that it is not useful to trace differences between conditions (ΔM) which are smaller than about 0.1 of the standard deviation of the residual error variation (due to the small power) even if large sample sizes are used. Such small effects can adequately be considered as non-existent as their eventual presence cannot be confirmed with a reasonable power even under strictly controlled laboratory conditions.

If an observed difference falls within the region between 0.1 SD_e and the magnitude of the chosen indifference margin, it should be qualified - by convention - as being non-interesting. In the study, the term "slightly different" is used to reflect the possibility that in the case of multiple comparisons among conditions, several succeeding "non-interesting" differences can accumulate into a difference (between conditions which lie relatively far apart) of such a magnitude that it exceeds the magnitude of the chosen indifference margin. As a consequence, the outcomes of workload assessments (if based upon a comparison between different conditions) can be categorized by one of the three aforementioned qualifications. That is to say, the workload levels at different conditions can be qualified as being either mutually "identical", "slightly different" (i.e. practically indentical), or (clearly) "different".

Now it is important to determine for each measure the magnitude of (the standard deviation of) the error variation (SD_e in figure 6) which remains after all tracable effects (from the experimental variables, from interactions between factors, and from covariates) have been filtered out. The more we can reduce this random variation in the data, the smaller the magnitudes for the indifference margins can be chosen (if it is desirable).

The determination of the magnitudes of SD_e for different measures needs the utilization of a research aircraft for the recording of the relevant parameters. Subsequently, also an extensive statistical analysis process is needed for filtering out the (non-random) effects of the experimental variables.

Once, the magnitude of the error variation is known for a specific variable, it can be used as a environmental "given" for assessments under similar operational conditions. Consequently these values can be used as a guideline for the determination of the criterion values with respect to the foregoing three assessment categories. Table 3 presents the derived SD_e values for some workload measures considered in this investigation (The criterion value of the model parameter E has been based on a comparison with subjective ratings for the pertinent task conditions). In this way, separate assessments can be obtained from the individual measures (if they are sensitive enough) for pairwise comparions between conditions. With respect to the possible outcomes, for instance concerning the workload (WL) involved in conditions A and B, the following notation will be used:
WL(A) "<" (or: "$\leq$", "=", "$\geq$", ">") WL(B). This notation, and the corresponding pictorial representation is shown in more detail in figure 7.

Now, in order to combine the separate outcomes of individual measures to obtain the final assessment, it is necessary to valuate the individual outcomes, for instance by means of a five-point scale ranging from -2 for the situation WL(A) < WL(B) upto + 2 for the situation WL(A) > WL(B). This commonly used valuation scale has also been applied in this study. The final assessment can subsequently be based upon the sum of all individual scores (each referring to a different measure), expressed as a percentage of the maximal attainable score. (for which situation the individual outcomes are unequivocally either ">" or "<"). As criterion percentages for deciding between "similar" and "slightly different", and between "slightly different" and "different", are chosen the values of 30 percent and 60 percent, respectively . (This relatively simple decision strategy is based, among others, upon the experimental finding that no serious contradictions occurred ($\{WL(A) > WL(B)\}_{measure\ i}$ against $\{WL(A) < WL(B)\}_{measure\ j}$).

The resulting final workload assessment with respect to the dual pilot approach tasks is presented in figure 8 (which is based on subjective ratings of subject pilots and safety pilots, and on the heart rate of the subject pilots as these were the only measures which could cover the whole range of taskconditions).

The final assessment with respect to the single pilot versus dual pilot conditions is presented in figure 9. (This assessment is based on the aforementioned measures, and on "error rates" reflecting the accuracy of the cockpit work). The results, which are of course open to future adaptations, can be used as a basis for collating and integrating the results of other workload assessment techniques.

Helicopter instrument flying experiment

Experimental program

The experimental study has been carried out in 1976 as part of a research program for the Royal Netherlands Air Force (Refs. 7,8). The aircraft used was an Alouette III helicopter which had been modified for the instrument flying tasks and for the measurement and recording of the relevant experimental parameters. The instrument flying tasks consisted of hovering at 600 ft above ground level (AGL) with minimal horizontal (ground) speed and of flying along a track of approximately 6 NM with an indicated airspeed of 60 kts, at either 600 ft or 150 ft AGL. (These latter tasks are referred to as the high navigation and the low navigation tasks, respectively). The instrument information consisted of the three attitude angles (provided by a three-axis ADI), height deviation, horizontal velocity components (in case of the hover task and indicated by the flight director bars) and cross-track deviation (in case of the navigation tasks and indicated by the vertical flight director bar).

Four military helicopter pilots participated as subject-pilots in the experiment. Besides, a safety pilot was responsible for the flight-operational aspects of the measurements. Each experimental sortie included two 3-minute hovering runs, and four 5-minute navigation runs (150/600 ft). Subjective ratings were requested after each run. To prevent outside view during the instrument flying tasks, a yellow screen was installed and the subject-pilot was wearing blue goggles (Figs. 10 a,b). In total 24 sorties were completed. The workload measures included in this investigation are summarized in table 4.

Results

Some important results from the helicopter flying study can be summarized as follows:

- A factor analysis of the data to indentify different (i.e. orthogonal) dimensions constitued by combinations of measures from different modalities, showed no indication for a common dimension which could characterize the whole set of data with loadings from all four modality groups of measures (i.e. physiological, subjective, performance, and control activity). Moreover, different tasks (navigation, hover) result in a different composition of the dimensions (see tables 5, 6). So, although a combination of different measures offers the best possibilities to quantify a complex concept like workload, there is no indication in favour of a superior combination.

- Similarly, large intercorrelations among the data from different measures have been found. The intercorrelation matrix, however, shows a different pattern for different tasks. This indicates that the considered measures tend to result (on the average) in similar outcomes, but their sensitivity seems to be dependent upon the task in which they are used. (This finding indicates also the need for an examination of the specific sensitivities of the measures - according to the rules outlined in the first study - before arriving at final conclusions).

- The hover task has been assessed as the most demanding task, followed by both navigation tasks at an identical workload level. This conclusion has been based upon subjective ratings, heart rate variability scores (RMSSD and log ABP), and respiration frequency which did discriminate the best between the tasks (Ref. 7), as well as upon an model analysis (control effort parameter E; Ref. 8).
Besides, the strength of association between the data from different measures appeared to be larger in a relatively high workload task condition (hover task) than in a relatively low workload tasks (navigation tasks).

- Control activity measures and skin resistance/conductance measures appear to the least discriminative with respect to workload aspects. Especially in a relatively high workload situation it apprears that they constitute a separate group of measures (see table 6).

- Finally, table 7 shows the average values for most parameters related to the three task conditions. The underlined results concern measures which are also considered in the first study. The table shows that the indifference margins derived in the approach study (namely 2.5 b.p.m. for M heart rate, 0.2 b.p.m. for RMSSD heart rate, 0.3 for the demand scale and 1.0 dB for the control effort parameter E), would also be a useful reference criterion for deriving conclusions from the helicopter flying tasks: a final workload assessment of tasks based on these four measures according to the rules set forth in the foregoing would lead to the same conclusions as drawn in the helicopter flying investigation.
Note that the performance index J indicates the same conclusion. The results from other measures (e.g. SCL, SSR, and safety pilot rating) do not indicate such a pronounced differentiation in workload between the hover and the navigation tasks. Whether this is due to a reduced sensitivity of these measures or not, could not be traced anymore. (The discussions in references 7, 8 suggest a reduced sensitivity, due to interaction effects, as a possible cause).

CONCLUSIONS AND RECOMMENDATIONS

The workload measures considered in both studies tend to give rise - in the case of a sufficient sensitivity - to similar outcomes (There were no serious contradictions found between the individual results of different measures).

All measures have their specific deficiencies. Therefore the simultaneous use of different measures is needed to increase the reliability of the assessment.

The sensitivity of several workload measures seems to be dependent upon task related aspects. This is especially apparent under relatively low workload conditions. It is therefore recommended to assess the sensitivity of each measure first (e.g. on basis of observed interactions between different variables, or based on effects of intervening variables) before drawing conclusions. Subsequently, it can be expected that a relatively simple decision strategy will already be sufficient with respect to the formulation of the final conclusions (based on different measures).

It seems satisfactory to formulate the conclusions (concerning possible differences in workload between different task conditions) on the basis of the categorization "non-different", "slightly different", or "different". These categories are related to so-called "indifference margins" with respect to the observed variation in the data.
Subsequently the drawing of an "overall" conclusion in which the individual outcomes of several measures have to be integrated can be based also on a relatively simple decision strategy. The criterions for these decision strategies are stated by convention. These criterions should eventually be refined in future investigations. Also, the utilization of a weighting function with respect to the separate outcomes of individual measures is to be considered in future investigations.

Measures based upon subjective ratings (McDonnell's demand scale) and heart rate level appear to be suitable for utilization in a wide range of tasks. The overall performance index J and the control effort (model) parameter E (Ref. 6) seem also to be useful workload measures for manual control tasks which can adequately be specified in model terms. Skin resistance measures and control activity measures seem to be less adequate as workload indicators. The usefulness of measures of heart rate variability and respiration frequency (in non-verbal tasks) should be considered further.

There is a clear need to include more measures of different modalities within a matrix of workload measures. Such measures should preferably be sensitive to workload aspects for a wide variety of tasks.

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TABLE 1
Task conditions for the fixed-wing aircraft approach experiment

Task Condition	Control Mode	Number of Crew Members	Approach Aid
a	Autopilot	2	ILS+FD/AP
b	Manual	2	ILS+FD
c	Manual	2	ILS
d	Manual	1	ILS
e	Manual	2	VOR+DME
f	Manual	2	NDB
g	Manual	1	NDB
h	Manual with trim malfunction	2	NDB

TABLE 2
Considered workload measures in the fixed-wing aircraft approach study

Pilot Ratings
1. McDonnell's 10-point demand scale (Ref. 2, Fig. 3)
2. SWAT 3x3 rating matrix (Ref. 3)
3. Pre- and postexperimental ranking of task conditions

Physiological Measures
1. Heart rate: basic statistics of the instantaneous heart rate (M, SD, RMS, RMSSD)

Primary Task measures
1. Task performance (flight accuracy)
2. Control activity: basic statistics

Model Measures
1. Control effort (Ref. 6)
2. Task "busyness" (Ref. 5)

Other Measures
1. Cockpit work accuracy ("error" frequencies)

TABLE 3

Magnitudes of the standard deviation of the (residual) error variation for a variety of workload measures

MEASURE	SD error
Task Demand ratings* (10-point scale)	0.33 (0.50)
SWAT ratings (100-point scale)	7.5 (8.5)
M Heart rate (b.p.m.)	2.5
RMS Heart rate (b.p.m.)	3.0
SD Heart rate (b.p.m.)	0.5
RMSSD Heart rate (b.p.m.)	0.2
Control Effort (E) model parameter (dB)	1.0**

(..): safety pilot ratings

* McDonnell's demand scale

** Corresponds - in model terms - to circa 20 percent reduction in the attention

TABLE 4

Measures considered in the helicopter flying experiment

Pilot ratings
1. McDonnell's 10-point demand scale (Ref. 2, Fig. 3)
2. Task effort 10-point scale (only the numbers 0 up to 10 are indicated in this scale)

Physiological measures
1. Heart rate: basic statistics; average band power (ABP) in the frequency band .06 to .21 Hz
2. Respiration frequency: the average number of inhalations per minute.
3. Skin resistance measures: resistance response (SSR) and resistance/conductance level (SRL/SCL)

Primary task measures
1. Performance index J:

$$J_{hover} = (\text{RMS } h/h_L)^2 + (\text{RMS } v_h/v_{h_L})^2$$

$$J_{nav} = (\text{RMS } h/h_L)^2 + (\text{RMS } y/y_L)^2$$

in which: h = height error, v_h = horizontal speed, y = cross-track deviation, L = display limit

2. Control activity: longitudinal cyclic control input (δ_e), lateral cyclic control input (δ_a) tail rotor pedal control input (δ_r) and collective pitch control input (CP)

Model Measures
1. Control effort (Ref. 6)

TABLE 5

Rotated factor matrix for the different variables of the navigation tasks (4 subjects, 42 runs). Only variable-factor correlations > .40 are given (ref. 7)

	Variables	Factors				
		1	2	3	4	5
1	Heart rate	.60			.71	
2	Root mean square successive difference (RMSSD)		.58	.58		
3	Log average band power (log ABP)				-.73	
4	Respiration frequency		.58		.72	
5	Skin conductance level (SCL)			-.85		
6	Skin resistance response (SRR)			.82		
7	Overall performance index (J)		.43	.55		
8	Safety pilot rating				.76	
9	Effort rating		.93			
10	Demand rating		.85			
11	Longitudinal cyclic control activity (σ_{δ_e})	-.90				
12	Lateral cyclic control activity (σ_{δ_a})					.93
13	Directional (pedal) control activity (σ_{δ_r})	-.85				
14	Collective pitch control activity (σ_{cp})	-.53				

TABLE 6

Rotated factor matrix for the different variables of the hover tasks (4 subjects, 33 runs). Only variable-factor correlations > .40 are given (ref. 7)

	Variables	Factors				
		1	2	3	4	5
1	Heart rate	.70				
2	Root mean square successive difference (RMSSD)				.88	
3	Log average band power (log ABP)				.72	-.57
4	Respiration frequency					.77
5	Skin conductance level (SCL)			.94		
6	Skin resistance response (SRR)			-.86		
7	Overall performance index (J)				[illegible]	
8	Safety pilot rating	.60				.63
9	Effort rating					[illegible]
10	Demand rating					[illegible]
11	Longitudinal cyclic control activity (σ_{δ_e})		[illegible]			
12	Lateral cyclic control activity (σ_{δ_a})		[illegible]		[illegible]	
13	Directional control (pedal) activity (σ_{δ_r})		.84			
14	Collective pitch control activity (σ_{cp})		.47			-.47

TABLE 7

Average values of various workload measures for the helicopter flying tasks (Refs. 7,8)

MEASURE \ TASK	Nav.-High	Nav.-Low	Hover
M heart rate (b.p.m.)	77.8	77.7	87.4
RMSSD heart rate (b.p.m.)	2.0	2.1	1.8
log ABP (-)	0.8	0.8	0.7
Respiration freq. (inh/min)	18.0	18.3	19.8
SCL (μMho/cm^2)	36.8	38.1	34.2
SRR (kΩcm^2)	0.27	0.22	0.28
Safety pilot effort rating	3.5	4.8	5.6
Subject pilot effort rating	4.9	5.4	6.2
Subject pilot demand rating	5.5	5.7	6.6
Control Effort (dB)	15.1	15.0	16.5
Overall performance J (-)	0.25	0.20	0.95

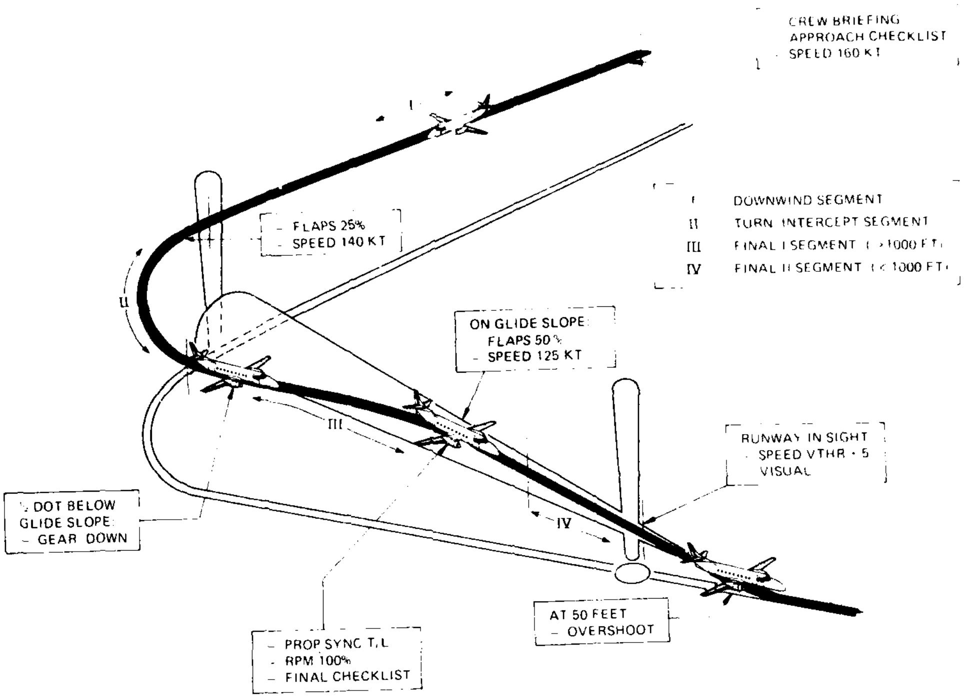

Fig. 1 ILS approach

Fig. 2 NLR Metro II research aircraft

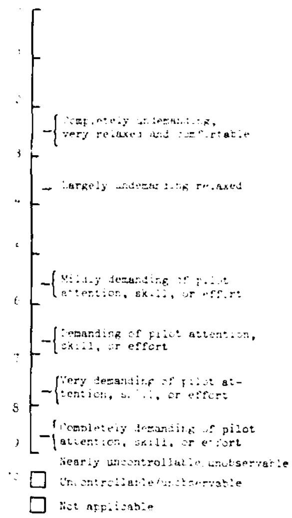

Fig. 3 McDonnell's 10-point rating scale for task demands on pilots

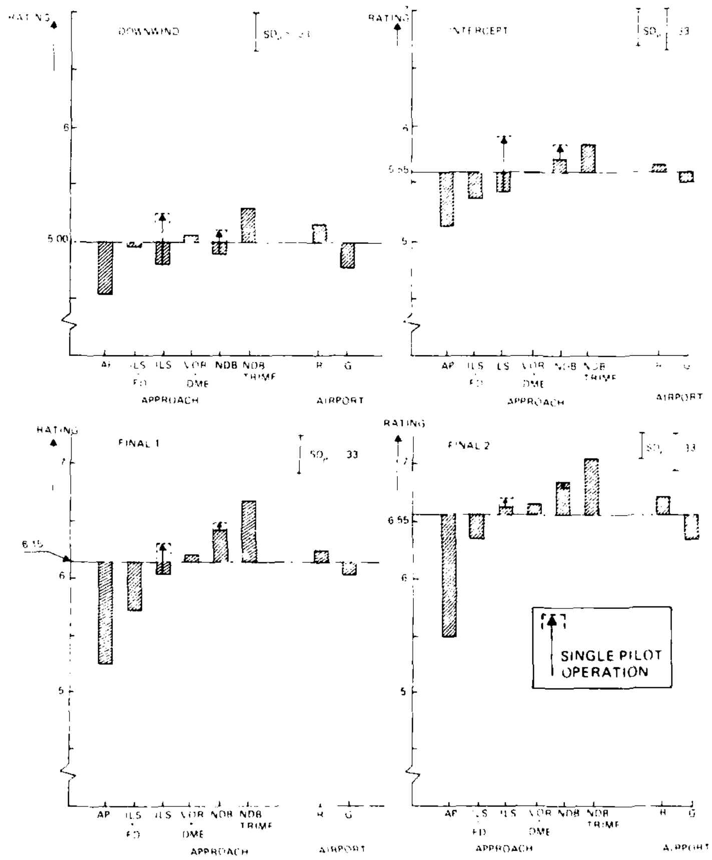

Fig. 4 Results of subjective ratings for the approach tasks (McDonnell's 10-point demand scale)

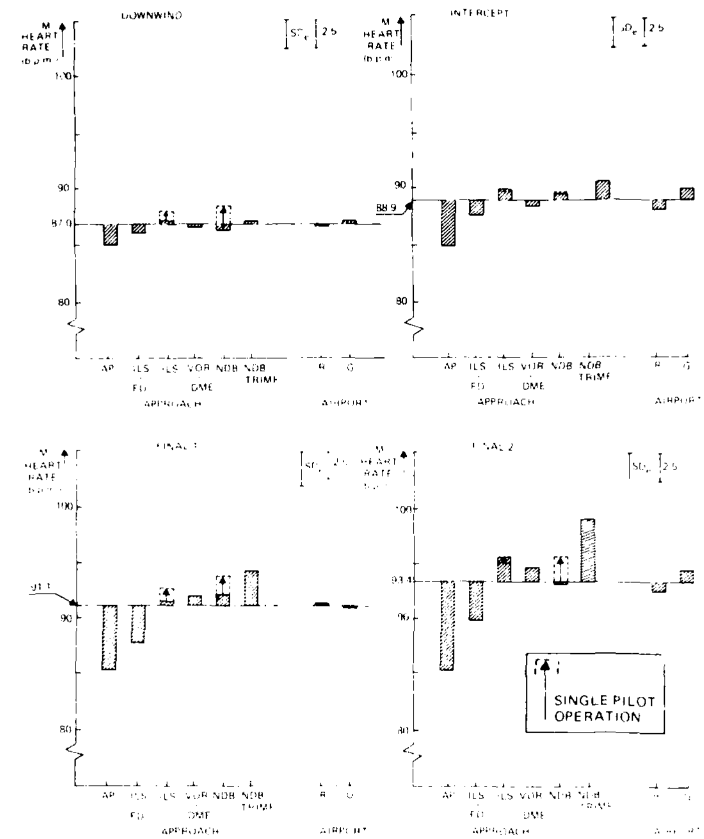

Fig. 5 Average heart ra results for the approach tasks

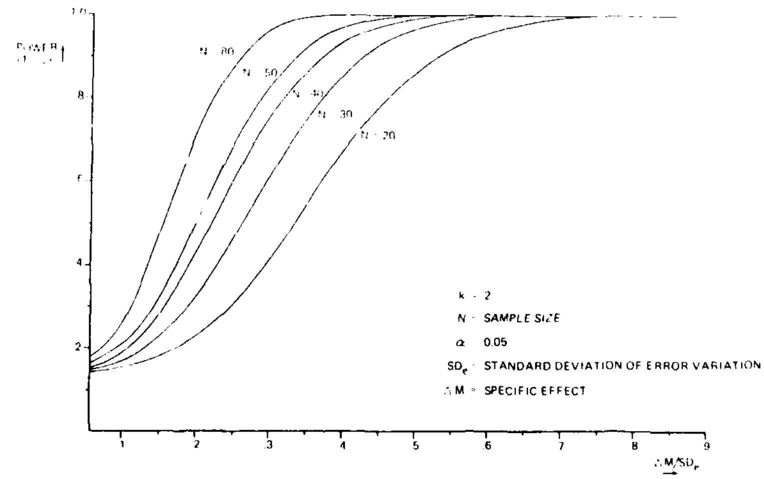

Fig. 6 Power functions for analysis of variance F-tests involving two conditions (k=2) for various sample sizes

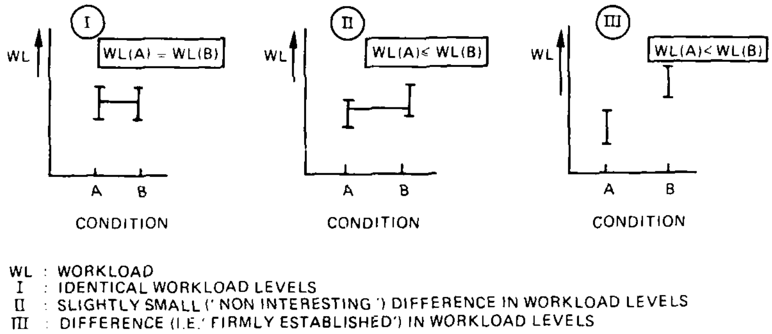

Fig. 7 Pictorial representation and corresponding notation (inserts) of the categorization of workload assessment results

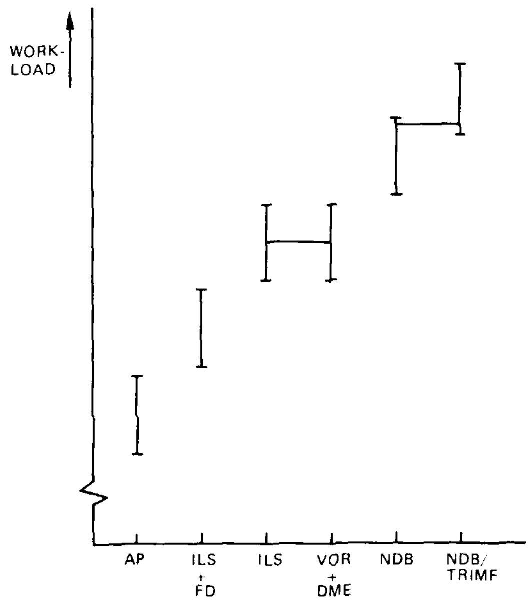

Fig. 8 Final workload assessment for the dual pilot approach tasks

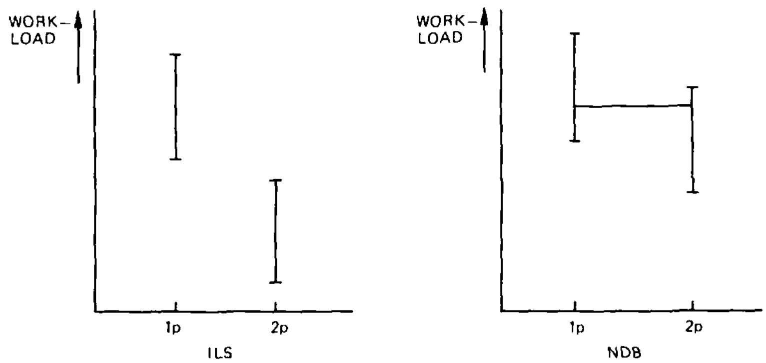

Fig. 9 Final workload assessment for the single pilot versus dual pilot approach tasks

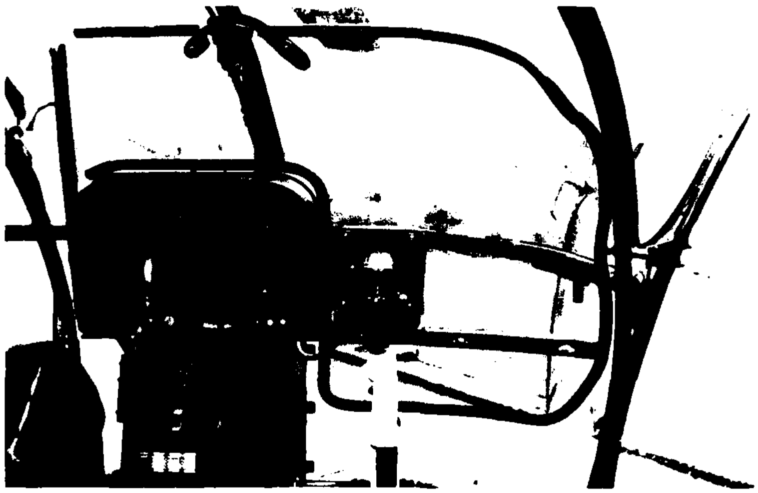

Fig. 10a General lay-out of the instrument panel and mounting of the yellow window-panel (Ref. 7)

Fig. 10b Safety pilot, subject pilot (with respiration sensor and blue goggles) and NLR observer (Ref. 7)

ADVANCES IN WORKLOAD MEASUREMENT FOR COCKPIT DESIGN EVALUATION

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SUMMARY

The stressful mission environment for tactical aircraft in the 1990's will require improved integration of pilot and machine to assure successful operations. A key to these improvements will be the development and proper use of combat automation to control and reduce pilot workload. Concepts such as decision aiding, automation of fire/flight control, on-board terrain data bases, and sensor fusion are but a few of the technologies that will potentially contribute. The selection of technologies for full-scale development and final integration in new aircraft, and upgrades to current ones, will require trade-off of cost and effectiveness. Techniques for quantitative measurement of pilot workload and performance are needed to assist in this selection and ensure that final cockpit integration does indeed result in reduced workload and improved overall pilot/vehicle effectiveness.

Research at the Armstrong Aerospace Medical Research Laboratory (AAMRL) has focused on the development of these quantitative pilot performance and workload measures. Improved methods for defining pilot functions, tasks, and performance variables have been developed along with test design and data analysis techniques to support cockpit evaluations. Significant advances in the measurement of workload have been made over the last several years using subjective and neurophysiological techniques. Research on measures of pilot situation awareness and decision making, critical toward understanding the pilot interface with automated systems, is underway. The approach in these efforts at AAMRL has been to establish a solid base of Laboratory research followed by the test and evaluation of measurement techniques in complex flight simulators and then actual flight experiments. Finally, technology has been packaged into computer-based aids and instrumentation systems so that they can be transitioned to the cockpit development and design community.

INTRODUCTION

The tremendous strides in sensors, communications, and electronics, to name a few, applied to the development of advanced combat automation will allow the modern pilot to become a tactical battle manager, significantly reduce his overall workload, and improve the mission effectiveness of our future tactical aircraft. True? We all hope that it is, but it is more accurately a statement of the objective of design and not a given outcome. Rather, new combat automation technologies will allow the opportunity for exciting new cockpit design options, but also significant challenges with respect to technology selection, detailed design and cockpit integration. Some early applications of automation technology indeed have resulted in workload problems reportedly due to poor display of relevant information and a lack of pilot confidence in the system that was designed to help him. Pilots have allegedly "turned the black box off" as a result of these integration problems. Clearly, this is not a desirable outcome of the design process, particularly since properly integrated automation should help the pilot, and indeed may be essential to safely and effectively accomplish missions under difficult conditions such as low level, high speed, night, in weather, and in high density threat environments. Quantitative methods for design evaluation that consider both mission and pilot performance are required to ensure proper cockpit integration.

For most complex design problems, measurement of actual performance and comparison with desired performance is an iterative process as the design evolves and shortcomings are fixed. This is not necessary if system elements have known models or performance characteristics, in which case the design can be determined analytically and the actual performance predicted with good reliability. Note, however, that quantitative predictive models of human information processing and cognition do not currently exist. Traditionally cockpits have been designed by yet another method that can best be described as the subject matter expert approach. Here, designers that are familiar with past practices and their good and bad features, extrapolate a new design and often consult the opinions of the users, that is the pilots. This works well where new requirements are not significantly different from the past. It is argued that this approach is not sufficient to meet the challenges of "the Man/Machine Interface in Tactical Aircraft Design and Combat Automation," which is the subject of this symposium. The emerging technologies mentioned earlier and their innovative use in combat automation will change the traditional role of the pilot. Therefore, cockpit design and the integration of combat automation will have to rely on quantitative methods to measure goodness and performance of the various options. Indeed quantitative measures of design goodness will help replace some of the art in cockpit design with engineering practice.

MEASURES OF GOODNESS: MULTIDIMENSIONAL ASPECTS

In the end, a tactical aircraft's worth is measured by its survivability and ability to deliver weapons on targets. Combat automation, other aircraft systems, the enemy, environment, mission objectives, and of course the pilot contribute to this overall effectiveness. Toward that end the pilot's performance of mission tasks must be measured as it relates to cockpit and automation options. In general, these measures are in terms of accuracy, timeliness, and probabilities of actions. On the surface then pilot performance measurement seems easy, first specify the tasks, then the appropriate measures, run a test, and analyze the data. Several factors complicate this process however.

Pilot functions and tasks are difficult to formally specify and many of them involve complex processes such as problem solving, planning, and decision making. A very useful framework for levels of human behavior was developed by Rasmussen (ref. 1) (Fig. 1). Skill-based performance involves sensory-response activities, for example control of the aircraft flight path over easy terrain. Rule-based performance involves complex series of actions such as the execution of a weapon delivery sequence in a

ground-attack mission. Finally, knowledge-based behavior is characterized by unknown situations, decision making and planning. An important role of the pilot in today's and any future aircraft is to handle uncertainties such as threats, weather, malfunctions, and changes in mission objectives, which is characteristic of the knowledge level. Measurement of this performance is difficult. What is the probability of making a good decision, assessing the situation correctly, making an error?

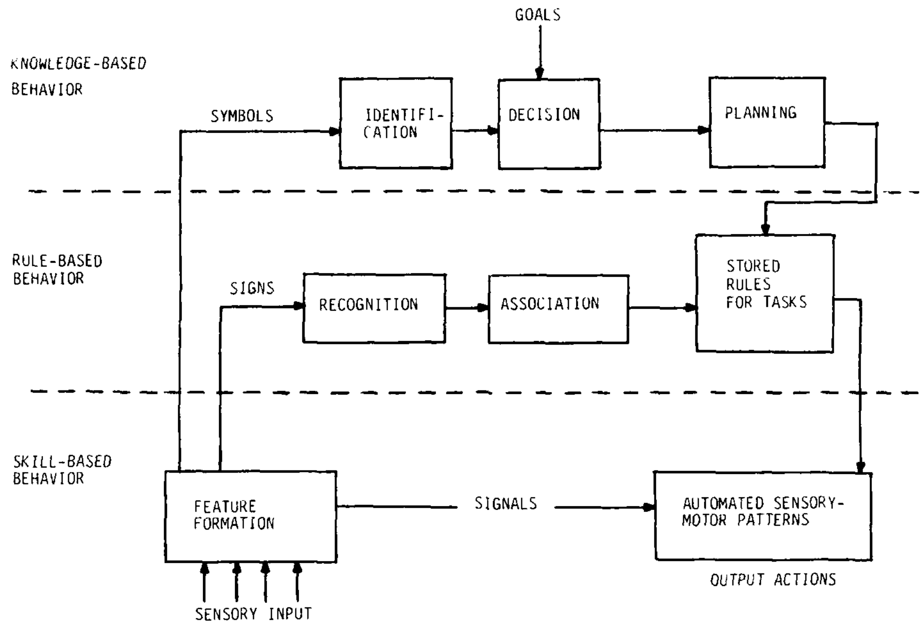

Figure 1. Levels of Pilot Performance

Other factors affect or help shape a pilot's performance of these complex tasks. The imposed demands of the mission (goals, environment, scenario, aircraft design) combined with personal characteristics (capabilities, skills, experience, biases) result in his level of workload. The concept of workload stems from the psychological construct that humans possess various mental resources which are depleted during the performance of tasks. As functions are automated in future aircraft, pilots will still be responsible for monitoring the health and status of this automation. The attention required for this new function must be compared to the benefits of the automation. Does the level of pilot workload really matter as long as the mission gets performed? Yes, in the same sense that we design electronic circuits within their capacity to handle required power levels. Components that operate outside design ranges have higher probabilities of failure. To carry this analogy to its end, heat is probably not a performance variable for the circuit, voltage or current is of interest. For the pilot, workload is a necessary variable to be factored into the design problem.

The use of machine intelligence technology in future combat automation will require an assessment of pilot confidence in the system. This will reflect how well system state, dynamics, and even limitations are understood by the pilot. This type of information may have to be displayed to enhance confidence and trust, so that the pilot will properly rely on the advice and performance of the machine aid.

Pilot physical and psychological state variables affect task performance as well. Some examples are levels of fatigue, the effects of acceleration, and combat stress just to name a few. These are essentially initial conditions and also must be measured or known in order to make assessments of overall pilot performance.

Assessment of the goodness of combat automation and cockpit integration requires the measurement of multidimensional aspects of pilot state and performance. Research at AAMRL is focused toward the development of measurement methods and tools to aid in the evaluation of cockpit designs and combat automation alternatives. Some of the results of this research are summarized in the following sections.

SYSTEM ANALYSIS

A necessary first step in any design evaluation is system analysis. Formal descriptions of system performance goals, functions, structure and detailed design are a part of the analysis process. Electronics, aerospace, mechanical and most other engineering fields have evolved formal procedures and conventions for analysis. The field of human engineering, or human/machine system design, has traditionally

used techniques such as task analysis to support this process. These have not however been sufficiently formal and complete enough to capture goals, function allocation, information flows, and overall human/ system structure.

Research at AAMRL has resulted in the development of the User-Assisted Generic System Analyst's Workstation (GENSAW) to support a structured and disciplined human/machine system analysis. GENSAW will eventually provide a cohesive set of computer-based tools to aid systems description, performance data base management and analysis (Fig. 2). All of these capabilities have not been fully developed, but Version 2 of GENSAW has three tools which are currently available for use in cockpit design and evaluation.

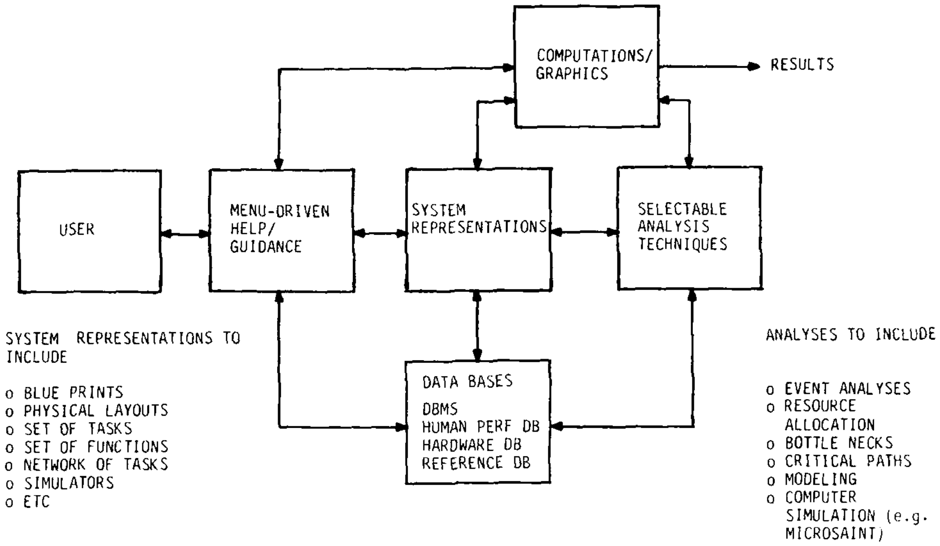

Figure 2. The GENSAW Concept

First, is a user-assisted Automated System Decomposition (ASD) program that allows one to develop a structured functional representation of a system. It uses a technique called IDEF (ICAM Definition, ICAM in turn is an acronym for Integrated Computer Aided Manufacturing) which was developed by the Air Force Wright Aeronautical Laboratory's Materials Laboratory (ref. 2). This is based on an approach from structured software definition and accounts for a system's functions, inputs, outputs, controls and resources. These features are very useful in describing human/machine systems such as a pilot's interface with his cockpit, aircraft systems, and outside environment. Controls represent constraints or guidelines in performance of a function such as, for example, tactical doctrine or other required operational procedures. Resources are the physical entities that actually accomplish the function which could be the pilot, combat automation, or other aircraft system. This feature provides a useful audit trail during design function allocation and the determination of performance measures. The ASD program allows a user to interactively decompose a system into parts starting from the top level mission function. The display screen graphically depicts the resulting human/machine function architecture. In addition, the performance measures that would be assigned to individual functions could be related to upper level functions and eventually overall effectiveness.

The ASD computer program also provides for the development of matrix data indicating the relationship between inputs, outputs, resources, and controls. Diagramming logic is checked automatically and tables, bar graphs, information traces, and the matrices can be displayed. ASD is currently hosted on a VAX 11/780 computer and a Micro Vax II Workstation.

An interactive computer-based analysis tool called the User-Assisted Test and Evaluation Methodology Assistant Program (TEMAP) has also been developed. This aids a user in management of a complex man-in-the-loop test and evaluation program, such as a full mission simulator evaluation of cockpit design or actual flight testing. The program actually uses IDEF to structure the steps of the test and evaluation. Each step is accompanied by helpful material on factors to consider, techniques, guidelines, solutions to problems, and applicable references. As a user specifies the details of the test and evaluation program, a data file is created that can be used to document the overall project. Examples of data to be specified are performance measures, numbers of test pilots, scenario details, and data collection schedule. TEMAP has been hosted on a VAX 11/780, MICRO VAX II Workstation, and IBM compatible personal computers.

The third computer program currently available is the User-Assisted Automated Experimental Design Program (AED). Proper specification of independent and dependent test variables for a complex evaluation in a full mission cockpit simulator can be difficult to accomplish manually. Interactions between

variables and confounds must be known. In addition, it may be more cost effective to run several small studies rather than one large test. AED allows a user to create or call pre-stored full and fractional factorial experimental designs. It is an aid for performance data management and obtaining statistically meaningful test results. AED is hosted on the same computers as TEMAP.

SUBJECTIVE WORKLOAD ASSESSMENT

The subjctive assessment of workload is an effective method particularly in operational and complex simulator evaluations. It is based on the premise that if an operator feels loaded and must use considerable effort while performing his tasks, he really is loaded and effortful. This may in particular be true prior to actual performance degradation when subjective feelings indicate the added effort that is being expended. Subjective measures offer the potential of being relatively nonintrusive to the performance of the primary mission tasks.

Research at the Armstrong Aerospace Medical Research Laboratory has resulted in the development of the *Subjective Workload Assessment Technique* (SWAT) (ref. 3). SWAT solves some of the historic problems with subjective assessment that suffered from limitations because of nonstandardized measurement scales. A technique called conjoint measurement is used to construct interval workload scales from purely ordinal rankings of subjective load levels. SWAT uses algorithms that are directly identified from the subjective data to represent the joint effect of several underlying factors. These rating factors have been adopted from a theoretical framework for workload assessment developed by Sheridan and Simpson (ref. 4). SWAT assumes that subjective workload can be represented by a combination of three levels of time load, mental effort load and psychological stress as defined below:

Time Load

1. No or very few interruptions in the planning, execution, or monitoring of tasks. Spare time exists between many tasks.

2. Task planning, execution, and monitoring are often interrupted. Little spare time. Tasks occasionally occur simultaneously.

3. Task planning, execution, and monitoring are interrupted most of the time. No spare time. Tasks frequently occur simultaneously. Considerable difficulty in accomplishing all tasks.

Mental Effort Load

1. Little conscious mental effort or planning required. Low task complexity such that tasks are often performed automatically.

2. Considerable conscious mental effort or planning required. Moderately high task complexity due to uncertainty, unpredictability, or unfamiliarity.

3. Extensive mental effort and skilled planning required. Very complex tasks demanding total attention.

Psychological Stress Load

1. Little risk, confusion, frustration, or anxiety exists and can be easily accommodated.

2. The degree of risk, confusion, frustration, or anxiety noticeably adds to workload and requires significant compensation to maintain adequate performance.

3. The level of risk, confusion, frustration, or anxiety greatly increases workload and requires tasks to be performed only with the highest level of determination and self-control.

Consider briefly the procedure for the application of SWAT to the evaluation of a particular cockpit/automation design alternative as implemented in a piloted aircraft simulator. Prior to actual simulator runs, the pilot subject pool is thoroughly briefed on the purpose of the study and then asked to develop overall rankings of the combined workload factors. That is, the 27 combinations of the three-dimensions and three levels for each are ranked from lowest to highest by each pilot. Numerical values for each combination are derived using the conjoint scaling procedure. The specific mission phases and tasks to be scored should also be determined prior to the data collection. Next during the actual simulation run, the pilot is asked to rate each of the three load dimensions for the event of interest. The pilot usually accomplishes this verbally following a verbal prompt by the experimenter. Some preplanning of this administration should be accomplished so that it does not interfere with the mission tasks and yet be taken temporarally as close as possible to the scenario event to be scored.

Both laboratory and applications research has been conducted to assess the validity of SWAT as a workload measurement tool. The stability of subject's judgment over time was measured in several studies. Thirty Air Force pilots participating in a study of air-to-air combat in a high fidelity simulator performed the ranking procedure four months apart. Predictions of the second ranking were 80% correct based on the original one. Another check was performed on twenty-two military subjects participating in a control room design evaluation. These checks were two months apart and all except one subject had ordering correlated .90 or greater. It can be concluded from these studies that subjects' internal model for workload is generally stabled over time.

Several independent studies have investigated the metric properties of SWAT. In a significant Laboratory study (ref. 5) involving over one hundred subjects SWAT data was collected on nine computer-based cognitive tasks, termed the Criterion Task Set (ref. 6) (Table 1). Parametric research has

established well defined loading levels for each task as well as training requirements and testing procedures. The results of this major study indicate that SWAT ratings were significantly different ($p < .05$) for the load levels on all the tasks.

Task	Processing Function
Visual Display Monitoring	Visual Perceptual Input
Continuous Recognition	Working Memory Encoding
Memory Search	Working Memory Storage/Retrieval
Linguistic Processing	Symbolic Information Manipulation
Mathematical Processing	Symbolic Information Manipulation
Spatial Processing	Spatial Information Manipulation
Grammatical Reasoning	Reasoning
Unstable Tracking	Manual Response Speed/Accuracy
Interval Production	Manual Response Timing

Table I - CTS Tasks and Associated Processing Functions

Other laboratory studies have investigated procedural aspects of SWAT. An experiment was conducted to determine the effect of a reporting delay of up to thirty minutes for three levels of loading on a display monitoring task (ref. 7). SWAT responses were not statistically different as a function of the response delay. A similar experiment (ref. 8) was run using short-term memory tasks. This type of task was chosen because subject recall of the actual SWAT ratings should also require the use of short-term memory, therefore constituting a more rigorous test. Again, however, the delay conditions did not differ significantly from the initial rating. Another experiment was conducted that explicitly varied the type and load level of intervening tasks between the one to be rated and the actual solicitation of the of the rating (ref. 9). Here, no significant differences were found as a function of the type of intervening task. All these studies indicate that delay in obtaining workload ratings, as may occur in operational situations, may not have a large impact on the overall ratings.

In addition to carefully controlled laboratory experiments, SWAT has been evaluated in flight simulators as well. A series of experiments on B-52 and F-16 ground-based high fidelity simulators have been conducted over the last three years (ref. 10). The degree of realism in these simulators make it possible to generalize the laboratory results to more real world situations. In one of these tests, line pilots from a B-52 squadron served as subjects and flew the flight simulator at Carswell Air Force Base, Texas. A scenario was constructed to have three different levels of piloting workload as follows:

Low: Straight and Level Flight
Medium: Normal Descent and ILS Approach
High: Descent to ILS Approach with Successive Engine Failures, Runaway Trim, and Crosswinds

Results of this experiment indicated that the SWAT scores clearly differentiated between the three levels of task demand.

Another simulation study used an F-16 simulator flying an air defense mission. This was a fixed base F-16D with essential controls and displays functional and a limited field-of-view outside visual simulation. Four defensive counter air scenarios were designed to capture from low to high workload as follows:

Low: An F-16 Chases three enemy aircraft making an "S" weave escape.

Medium Low: Five enemy aircraft approached the F-16 head-on.

Medium High: One enemy fighter approaches the F-16 head-on an S-weave pattern; two enemy fighters approach head-on; four enemy bombers approach the F-16 head-on behind the fighters.

High: Seven enemy fighters approached the F-16; two of the aircraft split in opposite direction to catch the F-16 in a pincher maneuver.

This experiment resulted in SWAT scores significantly different between high workload and all the others only, although the expected trend can be seen in the data (Fig. 3). Interestingly physiological and performance data had a similar result, indicating that there is perhaps not a significant overall workload difference between the first three levels. The whole series of studies, two of which were highlighted here only, provide good support for the sensitivity of SWAT to variation in task demand in complex simulators.

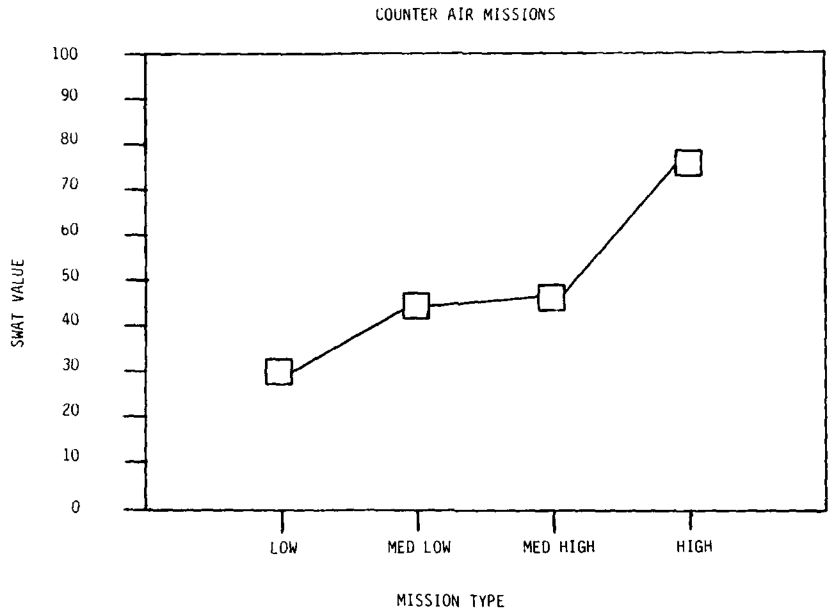

Figure 3. SWAT F-16 Data

The real objective for the development of a workload measure like SWAT is to provide a tool for use by designers to evaluate cockpit/automation alternatives in ground-based simulator and flight tests. SWAT has been applied extensively for this purpose by government and industry to evaluate design alternatives, procedures, and other various crew factors. Table 2 is a list of some of these evaluations.

Simulator	Operational
F-16/F-15 Air-to-Air	F-16 Flight Test
KC-135 Flight Deck Modernization	A-10 Flight Test
A-300 Approach and Landing	Laser Guided Missile Flight Test
B-52 Long Mission	
DC-10 Approach and Landing	
B-52 CG/Fuel Level Advisory System	
Helicopter Nap-of-the-Earth	
General Aviation Training	

Table 2 - SWAT Applications

A personal computer version of SWAT (PC SWAT) along with a detailed user's guide is now available. Required equipment is an IBM PC or compatible, 512K internal memory and two floppy disks or one hard and one floppy disk. The program supports analysis of data for up to 30 subjects.

NEUROPSYCHOLOGICAL WORKLOAD TEST BATTERY

The use of the body's physiological signals to assess mental workload has some promising features. First, if the signals can be easily obtained, it could be relatively unobtrusive, that is the pilot could perform the actual mission tasks without interference. Secondly, the measure may be rather immediate, allowing assessment of workload in narrow time intervals, as may be needed in rapidly changing tactical aircraft scenarios. Historically, however, they have not been very successfully applied. Experimental results were inconsistent depending on task and environment, all measures were equated in terms of providing an overall level of "arousal," and there were many differences between individuals. As a result of research sponsored by the USAF and others, selected measures of brain electrical potentials, eye blink and heart rate have emerged as useful indicants of mental workload. These selected measures have been

incorporated into a computer-based measurement and analysis system called the Neuropsychological Workload Test Battery (NWTB) developed by AAMRL (ref. 10).

Research over the past three years has been aimed toward evaluating the measures and NWTB system in Laboratory, flight simulator and limited field settings. Systematic laboratory experimentation using several of the standard cognitive tests of the Criterion Task Set has been accomplished (ref. 11, 12). In general, it was found that components of the brain electrical evoked potential varied systematically with workload levels on the different tasks. The evoked potential is the brain's response to a discrete stimulus such as an auditory or visual input. The eye blink closure durations in general were shorter when subjects were performing the tasks versus a no-task resting condition. The eye blink data did not however discriminate between loading levels on the tasks. Taken as a whole heart rate was not sensitive to workload levels on these laboratory type tasks. At first glance, these results may not seem very supportive of the utility of physiological measures. It will be shown in the discussions to follow on simulator and flight testing that the important point is that the proper measurement be selected with regard to sensitivity and time responsiveness.

Ground-based flight simulation is an important tool for the evaluation of cockpit and automation design alternatives. Because of this, the measurement of workload in these contexts is important. To support the development of such a capability, the NWTB was used to collect and analyze physiological data during the following B-52 and F-16 simulator exercises (ref. 10).

1. The pilot station of a B-52 flying an Instrument Landing System scenario which included three workload levels: straight and level flight, normal descent and approach, and approach with engine failures and crosswinds.

2. The tail gunner station of a B-52 involved in a hostile target encounter scenario with three levels of workload: high-altitude, low-altitude, low-altitude with radar system malfunctions.

3. Daytime and nighttime F-16 low-level interdiction mission with ingress, weapons employment and egress workload levels.

4. Weapon system operator station of a modified two-seat F-16 performing four air-to-ground weapon deliveries with varying levels of workload.

Measures of eye blink were emphasized during these tests and several of the parameters were clearly sensitive to the manipulations in scenario workload. These workload manipulations were determined to be valid based on their face validity to experts, that is pilots, and also a formal analysis and rating of type and level of demand imposed. The blink rate and closure durations both decreased as a function of increasing workload, in particular visual input load. These parameters were most sensitive when keyed to particular mission events and thus will be useful in evaluations that require time sensitivity.

A study of physiological measures of fighter pilot workload during actual A-7D training flights was also recently completed (ref. 13). Here brain electrical potential, eye blink, and heart rate data were collected for a battle area interdiction mission profile. The data were recorded on a miniature battery-powered device which fit in the pilot's flight suit.

Data was subsequently processed on the ground and analyzed by the NWTB. The A-7D mission required low-level high speed flight, navigation and weapons delivery. Results of this study have been very promising in that all the physiological measures provided useful information on pilot workload. Heart rate in this case appeared to index an overall level of workload and was not sensitive to G stress as were the other measures. Significant effects as a function of mission events resulted and also differences in the same pilot when flying the lead versus wing position. The flight environment provides interesting opportunities to observe real world type events. An actual bird strike occurred to one pilot after he had just cleared some power lines (Fig. 4). Note the pattern in the variability of the heart rate inter-beat interval as well as the heart rate itself. High workload after the bird strike was a result of aircraft damage assessment activities.

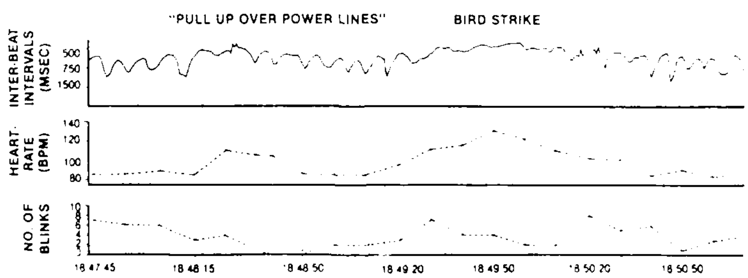

Figure 4. A-7D Physiological Workload Data

AAMRL has pursued systematic research and testing of physiological measures of mental workload for application to the design and evaluation of cockpit and automation alternatives. Results to date indicate that physiological measures have utility, but each has its own sensitivity to loading and temporal factors.

Although further research to determine specific rules for application is ongoing, a preliminary guideline based on our experience is as follows. The brain electrical measures allow detailed analysis of processing workload, but work best in well controlled laboratory settings. Eye blink measures have utility in complex simulators particularly where visual processing load is of interest. It also allows relatively fine grained time analysis of workload. Heart rate is a viable measure for use in limited flight tests where overall workload as a function of mission events is of interest.

SITUATION AWARENESS: AN EXAMPLE ANALYSIS

No one questions the fact that pilots must have good situation awareness to successfully accomplish missions. Also an important goal for new sensor, combat automation, and cockpit technologies is to improve pilot situation awareness. What is situation awareness and how do we know if it is improved, or degraded? Research at AAMRL has begun to address these issues and to develop quantitative measures of situation awareness needed for design evaluation.

Although situation awareness lacks a formal definition certainly many are possible depending on purpose. In order to provide a framework for our research, a working definition somewhat analagous to a state space representation of a dynamic system has been proposed (Fig. 5). Current state information includes geometry and status information, i.e., this is a pilot's knowledge of where he is in his mission, physical space, relationship to friendly and enemy forces, and also overall aircraft condition. In addition, knowledge of priorities, probabilities, future trends, and consequences of the current state is required. It is proposed that this total set of information and how it relates to the mission objectives represents situation awareness.

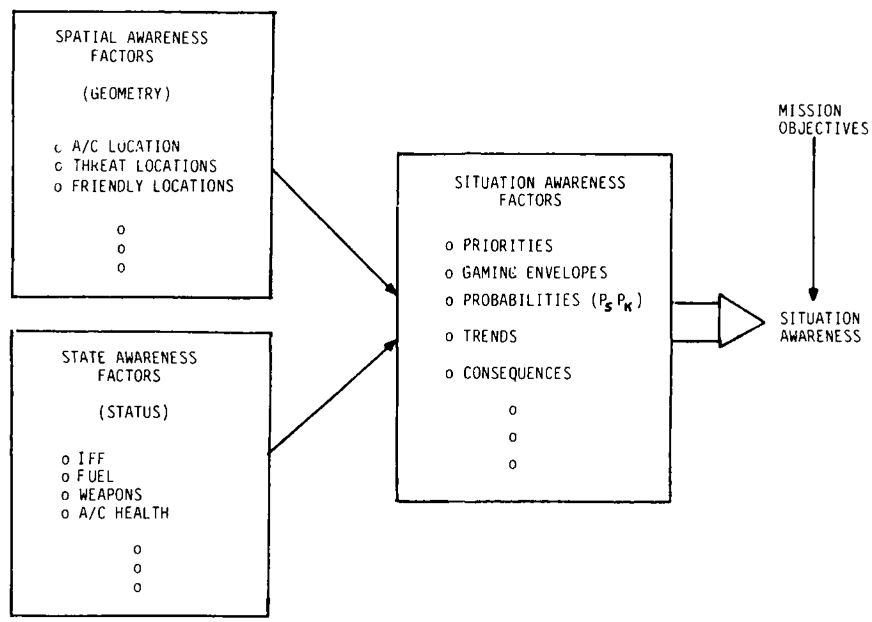

Figure 5. Pilot Situation Awareness

A measure of a pilot's degree of situation awareness should necessarily represent these multidimensional factors. Research at AAMRL has applied a statistical technique called multidimensional scaling (MDS) to investigate pilot performance and situation awareness, in simulated air combat maneuvering (ref. 14). MDS is a tool for studying the structure of data through measures of relatedness. This technique was applied to an existing performance data base obtained from thirty pilots during simulated one-versus-one air combat maneuvering free engagements. The performance measures are defined in Table 3. For this analysis, pilots were rated as expert or novice depending on their experience. The MDS maps for each are shown in (Fig. 6). The axes and respective scales reflect the dimensionality of the data, and require rather complex interpretation. For the purposes of this discussion points that are closer are simply more related. Experts had a well defined cluster on the left that was energy related. The cluster on the right represented air combat maneuvering variables. These pilots associated mission success with offensive and defensive maneuverability. The novice pilots lack these more well defined clusters. Note that gun kill was not strongly related to anything, perhaps a reflection of luck. Also, the mix of energy management variables with offense and gun range indicate a dependence on throttle activity for offensive air combat maneuvering. Numerous other insights can also be obtained from this data. To summarize, mission effectiveness data also indicated that the experts got more kills and used less fuel.

Performance Measure	Definition
Altitude Rate	Mean Absolute Vertical Speed
Roll Rate	Mean Absolute Roll Rate in Deg/Sec
Idle	Number of Times Throttle in Idle Position
Mil Power	Number of Times Throttle in High Mil Position
Speed Brake	Mean Speed Brake Deflection
Fuel Flow	Mean Fuel Flow in LBS/HR
Energy Mgt	RMS Energy Management Index
Start Position	Initial Simulator Configuration
Out of View	% Time Out of Opponent's View
Offense	% Time Opponent Positioned at a Single Angle of Less than 60 Degrees
Gun Range	% Time Opponent Positioned within Gun Range
Gun Kill	Probability of Gun Kill

Table 3 - Simulated Air Combat Maneuvering Performance Measures

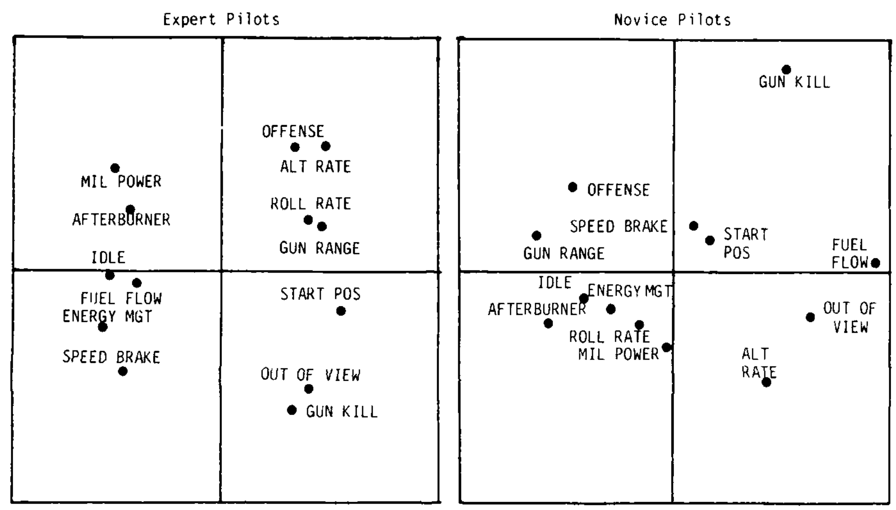

Figure 6. Air Combat Performance Space

This type of statistical technqiue allows the analysis of the complex dynamics of air combat and insight into the underlying pilot situation awareness. The same procedure could be used to evaluate the effects of combat automation options and cockpit designs on a pilot's ability to manage his overall situation awareness.

FUTURE RESEARCH

Many challenges remain to be solved toward the development of quantitative performance and workload measurement techniques for design evaluation. Future research projects at AAMRL will address some of these challenges. The Generic System Analyst's Workstation will be upgraded to include a network simulation capability. This will allow model prediction of mission performance from aircraft and pilot task data. A next generation Neuropsychological Workload Test Battery is in the early stages of development. This system will be ruggedized, include more automated data analysis and have a hardware/software architecture that allows improved interface with ground based simulation and advanced fighter flight testing. The multi-dimensional scaling and other approaches toward measurement of situation awareness will be refined in the context of design evaluation. A new initiative aimed toward assessment of decision making in the cockpit has also begun. This will develop measures of judgement variables, correct decision likelihood and error avoidance as an example. These new methods and tools will further refine the designer's ability to make quantitative evaluations of combat automation and cockpit designs.

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Moding Strategy for Cockpit Data Management in Modern Fighter Aircraft

by

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1. Introduction

In 1984 we presented a paper on "Cockpit automation requirements derived from mission functions data" /1/. This was the first step to develop a method by which the Cockpit Moding and the Cockpit Data Management can be established systematically. This first step included:

- Definition of the design driving mission.
- Breakdown of the mission into phases, segments and tasks.
- Assessment of operationally required levels of automation for information and control functions of tasks.

Meanwhile the method has been extended. It includes:

- Assessment of access time allowed for information elements and control functions.
- Differentiation of the mission tasks according to demand type (importance, frequency of use).

This method developed so far renders the "operational requirements" for the cockpit moding.

The steps of specifying the cockpit moding are as yet not so well defined. That is the reason why we used the term "Moding Strategy" instead of "Method" in the title of this paper. The paper deals with the method of deriving the operational requirements and with the subsequent tasks to be performed within the process of cockpit moding.

The design driving mission is not detailed in this paper. The criteria applicable to define and breakdown missions in different scenarios are dealt with in the Report of the GCP Working Group on "Improved guidance and Control Automation at the Man-Machine Interface" /2/.

In this paper data of the Air-to-Air combat mission phase, and thereof the medium range mode are used for exemplification of the method.

2. Deriving the Operational Requirements

The method used comprises tasks of different type. These are:

(1) Analytical Tasks

(2) Tasks to identify and scale assessment criteria.
Such criteria are forming the "rule base" for deriving the Cockpit Moding.

(3) Assessment Tasks.

(1) Analytical tasks

- Definition of Design Driving Mission
- Mission Analysis
  Breakdown into Phases, Segments, Tasks
- Identification of Operational and System Functions related to the Mission Tasks

- Listing of all Information Elements and Control Functions applicable to the Mission Tasks and Segments.
- The compilation into groups of elements/functions was already described in the 1984 paper /1/ and in /2/.

For the purpose of cockpit moding the information element grouping had to be extended as shown in Fig. 1.

(2) Tasks to identify and scale assessment criteria

- Access Time allowed per Information Element and Control Function related to the associated mission segment. Scale:

  o Essential Information for the mission task; immediate access required
  o Highly Desirable Information; reasonable access time allowed
  o Desirable Information; access time non-critical.

- Task Demand Type applicable to the mission tasks. Scale:

  o Priority task/function within the mission segment
  o Intermittently required tasks
  o Tasks to be performed continuously.

- Automation Levels applicable to the functions performed by task execution. These automation levels were already presented in /1/ and /2/. Applying the automation levels within the system engineering process required a slight modification of the scale. The levels are:

  1. Manual
  2. Manual augmented
  3. Manual augmented - Automatically limited
  4. Automatic-Manually limited
  5. Automatic-Manual Sanction
  6. Automatic

(3) Assessment tasks

The assessment includes:

- The information elements for access time allowance within the mission segments.

- The mission tasks and related functions for task demand type and automation level recommended.

The assessments require involvement of experienced user pilots/aircrews. It can be done in different ways: either by every pilot doing the assessment individually, or by having a group exercise.

The individual assessment has been applied by General Dynamics /3/ using specific questionnaire techniques. It also was done by MBB /1/ using a guided interview technique. These techniques render statistical results. We found these statistical results being a reasonable guideline. However, they are not easily to be transformed into operational requirements.

Therefore we chose a group exercise for an air-to-air mission application. The assessment formats are identical for both types, the individual and the group exercise. The group exercise has advantages and disadvantages.

Advantages:

- Individual opinions can be discussed and reinforced or turned down.
- The assessment results in agreed operational requirements.

The major disadvantage is the number of sessions required with all group members present. The exercise required 3 sessions for automation level assessment, 2 for access time assessment, and 2 to arrive at an agreed Cockpit moding concept, *the step which is described in the next paragraph.*

Fig. 2 shows the block diagram for the elements (1) to (3) of the method for deriving the operational requirements for the cockpit data management in an integrated avionic environment.

Fig. 3-a shows the summarised results of the assessment of the information elements for access time requirement. 61 of the 70 information elements requiring immediate access (or 87 %) in the combat phase are related to combat and threat management and to flight reference and the respective systems. Most of the 11 systems information elements are related to sensors, defensive aids and to the flight control system.

This information is required for the cockpit moding.
The access level requirements determine the moding hierarchy for the information elements and their relevant control functions.

Fig. 3-b shows the summarised results of the assessment of task demand types and automation levels for the tasks identified applicable in the medium range combat phase in an air-to-air mission.

Exemplifying information:

- Priority tasks are -in this phase- mainly combat and threat management tasks as target detection, assessment, prioritisation; situation evaluation, establishing attack procedures etc.
  A number of functions relevant in those tasks are initiated manually (Automation Levels 1 and 2), and controlled automatically (Levels 4 and 5).

- Intermittent tasks are defense management and C3I tasks controlled manually augmented.

- Continuous tasks are monitoring tasks concerning systems, resources, data link.

The group exercise rendered agreed ratings of the automation level operationally required for the mission tasks. These operational requirements form a sound data base for the discussions between cockpit and sub systems specialists concerning the functions specification for the sub systems.

3. Establishing a Moding Strategy

These operational requirements are one set of moding factors to be applied for the definition of the cockpit moding. Other moding factors have their origin in:

- The Man-Machine-Interface knowledge and rule data base
- Operational conventions and/or agreements
- The sub systems capabilities

A method to define the moding of cockpit systems, of displays and control functions was not developed as yet. Such a method would have to be

- based on defined principles
- performed step by step in a controllable procedure
- reproduceable and applicable to all kinds of aircraft/helicopter cockpits to be designed.

Fig. 4 shows the block diagram of the tasks to be performed in defining the cockpit moding, together with their interrelation:

(1) Operational requirements (para. 2):

- As.essment of access time allowance to information elements and control functions.
- Assessment of mission tasks.

(2) Operational conventions/agreement:

- Allocation of information packages to display surfaces for moding levels default, level 1 and level 2.

(3) Moding

- Define basic moding functions and principles.
- Define categories and moding of warning functions.
- Allocate control functions to devices.

(4) Identification of related subsystems functions

This task block refers to the interface between cockpit moding and subsystems specification.

In all tasks performed during the course of cockpit moding the associated subsystems functions must be identified. The requirements must be harmonised with the capabilities. This is an interactive task throughout the design and development process, and is not detailed in this paper.

The ergonomic requirements are shown in Fig. 4 as influencing set of conditions. They comprise ergonomie data, knowledge, rules, standards, and specifications applicable in the course of cockpit moding, which is only part of the total SOW task block of Man-Machine-Interface Engineering.

The allocation of information packages to the display surfaces is entitled "Operational convention/agreement" in Fig. 4. The reason therefore is: The requirements for allocating information packages to areas in the cockpit is not a specification item for sub systems. It is an operational requirement, to be established within the systems engineering process in direct cooperation with the user community, i. e. the pilots/aircrews.

To perform this task we used the following approach:

a) Develop a draft moding proposal based on data collected with the operational requirements assessments (para. 2):

- Information elements availability time requirement
- Information elements assigned to task groups (Flight Control, Navigation etc.)
- Evaluation of information requirements for mission phases

b) Assessment of the draft moding proposal in a group exercise with experienced user pilots - same group and procedure as described in para 2-(3).

In both steps, the development and the assessment of the draft proposal, information from previous and contemporary aircraft cockpits as well as from recent simulation experiments was taken into account.

The results of this exercise are the operational agreement of the basic moding requirements. A generalised example is presented here to illustrate the information load for the display surface in the 3 basic hierarchy levels of the moding.

The table (Fig. 5) lists the number of information elements (parameters) of the various information groups allocated to the display surfaces in the mission phase: Combat-BVR.

The information element groups used are the same as detailed in Fig. 1.

In other mission phases the allocation is considerably different. However, the relation between display and primary task resp. information allocation is kept constant. This is because a high consistency is required for the information allocation to displays.

The pilot must not be confronted with unmotivated changes of display contents or with specific information being displayed at different positions in different mission phases.

In general the information allocation in the BVR mode of the combat phase shows the following:

- BVR is a headdown operation, and there is no SEN or weapon STA information displayed in the HUD.
- The default level has high priority. Only the Right MFD allows certain switching to level 1 and 2.
- The HUD is used as the primay flight instrument.
- The Left MFD is the primary sensor and attack display.
- The Center MFD is the primary tactical management display.
- The Right MFD is used as multi-purpose display.

With the completion of this exercise the information allocation is sufficiently defined as far as the operational requirements are concerned.

Further definitions into a greater level of detail, and down to the subsystems functions level are subject to close coordination between the cockpit and the subsystems specialists.

Fig. 4 contains other task blocks we have not dealt with in this paper. These are:

- Moding definition
- Allocation of control functions to devices
- Warning categories and moding
- Subsystems functions identification.

The description thereof can not be included here.

These tasks are so far performed in a more heuristic approach. And there is no other way.

Further research is required to develop a systematic method, which can be used as a tool guiding the systems engineer through the process of cockpit moding.

Glossary

A/A	Air-to-Air
A/G	Air-to-Ground
C3I	Command-Control-Communication-Intelligence
CMFD	Center Multi Function Display
DASS	Defensive Aids Sub-System
GCP	Guidance and Control Panel
HUD	Head-up Display
IFF	Identification Friend Foe
JTIDS	Joint Tactical Information Distribution System
LMFD	Left Multi Function Display
POI	Point of Interest
RMFD	Right Multi Function Display
RWR	Radar Warning Receiver
SIF	Selective Identification Feature

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FLT Flight Reference Information

SEN Sensor Information
- A/A Radar
- FLIR
- Target (Range, Bearing, Altitude)

TAC Overall Situation Information
- Tactical Information
- RWR
- JTIDS/DASS
- Threat Assessment

NAV Horizontal Situation Information
- Navigation
- Mission Times
- Route and POIs
- A/G Radar (Mapping)
- Map

COM Communication
- Frequencies, Codes, Channels
- IFF/SIF Codes
- Authentication
- Clearances

STA Status Information
- ENGINE (ENG)
- Fuel Management
- Systems (Elect., Hydr. etc.)
- Configuration (War Load)
- Weapons
- Check Lists, Test

DAT Data
- Comms List
- Charts (Appr., Alternates)
- POIs List
- Callsign
  Authentication Format
- Arming Area, Barrier etc
- Flight Position

WNG Warning

Fig. 1 Information Classification for Display Moding

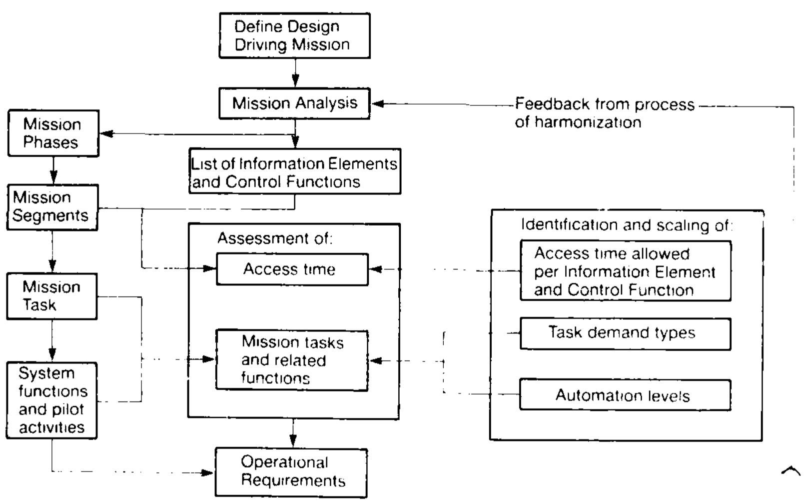

Fig. 2 Deriving Operational Requirements

Information Element Group	No. of Elements	Access Time Requirements/No. of Elements Immediate	Reasonable	Non Critical	n. a.	Warnings
Flight Reference	26	11	3	–	9	3
Navigation	36	5	5	1	25	–
Systems	83	11	23	21	17	11
C3I/Data Link	13	3	4	4	–	2
Combat Management	34	26	8	–	–	–
Threat Management	31	14	11	–	–	6
General	14	1	4	6	3	–

Fig. 3 Example of Deriving Operational Requirement

a) Assessment of Information Elements for Access Time Requirement

Tasks Demand Types	No. of Tasks of Segments	Condition	Automation Levels Assigned to Task: 1	2	3	4	5	6
Priority	30	initiation	7	10	–	7	5	1
		control	2	7	–	[illegible]	13	1
Intermittent	6	initiation	3	3	–	–	–	–
		control	1	3	–	–	2	–
Continuous	6		–	–	–	2	–	4

Fig. 3 Continued:

b) Assessment of Task Demand Types and Levels of Automation

Mission: Air-to-Air
Phase: Combat-Medium Range
Segments identified : 5
Tasks identified : 42

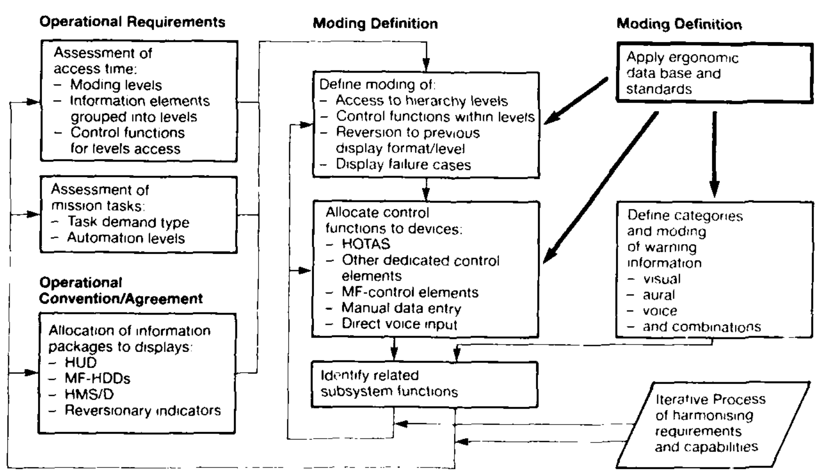

Fig. 4 Moding Strategy

Display Surface	Mode Level				
	Default		1		2
HUD	FLT	13	–		–
LMFD	SEN	8	DAT	3	–
	STA	3	WNG	nn	
	FLT	2	STA	1	
	TAC	1			
CMFD	TAC	10	TAC early Wng		–
	FLT	2	COM	1	
	STA	2			
	SEN	2			
RMFD	NAV	8	NAV	8	STA as required
			COM	4	DAT 2
			DAT	4	
			WNG	nn	

Fig. 5 Number of Information Elements per Information Group Allocated to Displays

A MAN-MACHINE INTERFACE SOLUTION: THE EAP GLARE SHIELDS

by
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SUMMARY

Continuous improvements in capabilities of military aircrafts require sofisticated navigation, communication and weapon systems. In the mean time pilots require to interact with these systems by using data entry facilities or synthetic data displays. Control panels using traditional push-buttons with fixed legend cannot be enough flexible to meet these new requirements. This paper presents an original solution to control the systems through an integrated alphanumeric keyboard facility using custom push-button matrix with programmable LED display legend. Design and development activities have been carried out by the authors and two equipments named LEFT and RIGHT GLARE SHIELDS are now operational on the EAP demonstrator.

INTRODUCTION

Cockpits of modern combact aircrafts are requiring many new man-machine interface in order to program and control systems and visualize synthetic information. Interactions between the pilot and these input/output systems need to meet requirements such as very limited space environments, HOTAS operations compatibility, enhanced capability in reconfigure the input/output functions and friendly interface with the crew.
As an answer to the above general requirement AERITALIA Avionics Systems and Equipment Group has developed, in collaboration with BAE Warton, two equipments named GLARE SHIELDS presently in use on the EAP prototype.
In general, the GLARE SHIELD is a shaped head-up mounted metal structure used to avoid the lost of contrast in the cockpit instruments due to incident sunlight.
In the EAP this feature still exist but the GLARE SHIELD mechanical structure contains a complete programmable data entry facility with sunlight readable alphanumeric display.

OPERATIONAL DESCRIPTION

The main task of the GLARE SHIELD is to provide the Manual Data Entry Facility (MDEF), a mean whereby system data and information can be typed-in, selected, displayed and updated using one common centralized and integrated device.
It fulfils the data entry functions of several dedicated units found on conventional aircraft allowing, in the EAP application, data entry to

- the Inertial Navigation Unit (INU)
- the TACAN
- the Communications Sub-system.

The MDEF takes on different functions by operating in 'Levels'. At the top level 0, five multi-function Sub-system Moding Keys (SSMKs) are available to allow re-moding to level 1 where data can be entered to the above sub-systems.
Alphanumerical data are inserted by using Data Entry Keys (DEKs) and displayed on two Read Out Lines (ROLs). The concept allows for many levels, but only two are used on the EAP.
Some control functions are carried out by using dedicated controls, i.e. comms channel selection and change destination.
The MDEF functions are implemented in two similar units, named LEFT HAND GLARE SHIELD

(LHGS) and RIGHT HAND GLARE SHIELD (RHGS), mounted in the upper part of cockpit (fig. 1) and connected to the Cockpit Interface Units (CIFU) throught a dedicated dual redundant 1553 Serial Data Bus (fig. 2) used to send pilot demand data and to receive display and moding data to be transmitted or received by the relevant sub-systems on the Avionic Data Bus (CAMU, INU, TACAN).
The LHGS (fig. 3) contains controls and displays. Controls consist of:

- Eleven System/Sub-system Moding Keys (SSMKs) used to select the required operations
- The Data Entry Keyboard (DEK board) used for data insertion
- A dedicated communication channel selector (including present/manual mode selector)
- Dedicated editing keys as ENT (enter) and CLR (clear)
- The three-position centre biased toggle switch for cursor positioning

and displays are:

- Dedicated Set and Destination Waypoint displays (SWP and DWP)
- Two Read Out Lines (ROLs).

The RHGS contains three display areas where are shown communications selected channel and frequency, the selected communication mode and TACAN selected channel, beacon mode and operating mode. The MDEF allows data to be entered to Navigation (Inertial Navigation Unit and Radio Navigation Aids) and Communications (Main Radio) sub-systems.

The navigation data to be entered are:

- Set Waypoint (SWP) number
- Latitude and longitude against Set Waypoint number
- Alignment latitude, longitude and true heading
- Time (hours, minutes, seconds)
- TACAN channel
- TACAN operating mode (receive only or transmit/receive)
- TACAN beacon mode (X or Y).

In addition, position fixing errors are displayed and accepted or rejected via the MDEF.

The Comms data to be entered are:

- Receiver mode (Transmit or Transmit + Guard)
- Narrow or broad bandwidth
- Operating channel/frequency entry
- Manual or present mode selection.

As above mentioned, LHGS and RHGS are software programmed to operate in levels (fig. 4). This feature takes advantage from the capability of the SSMKs and DEKs to change their legends and associate functions under software control in responce of pilot interactions. At the top level (level 0) SSMKs labels and functions are:

TIME - to initialise system time

ALGN DATA - to allow entry of alignment data to the Inertial Navigation Unit (INU)

COMM - to allow operating data to be entered to the V/UHF radio via the CAMU

SWP - to allow navigation waypoint data to be entered to the INU

TCN - to allow operating data entry to the TACAN.

The combined use of programmable legends, dedicated display areas, cursor marker, editing functions as clear, enter and restart allow flexibility and friendly interface with the operator.
As an example the COMMUNICATION mode data entry facilities are presented.
After the power-up, at the completion of the BIT procedure, the LHGS presents the level 0 display (fig. 5).
By pressing the SSMK with the legend 'COMM', the level 1 communication data entry facilities are selected and the LHGS display layout is presented to the operator (fig. 5).
When in COMM level 1, three data entry submode are available, the Destination and Set Waypoint display remain as previously programmed, the Change Destination 'CHD' switch is software disabled, the ROL 1 visualizes the word 'MANUAL' to indicate that the manual frequency change mode is selected and ROL 2 shows the previously stored manual frequency.
The Data Entry Keyboard becomes operative showing digits, clear and enter labelled keys allowing the operator to enter a new manual frequency by typing in the desired entire value.
If only partial correction of the actual value is desired the marker has to be positioned under the uncorrect digit by operating the cursor toggle switch and by pressing the new digit. When the switch labelled 'ENT' is pressed the frequency value displayed by ROL 2 becomes immediately operative only if the manual mode is also selected on the communication control switch. Otherwise the new manual frequency is stored and becomes operative whenever the manual mode on the CCS is selected.
The three available SSMKs on the top of the LHGS are programmed to act as momentary switches with toggle labels. They are used to select the optional mode of operation available and the current operative option is displayed with the appropriate mnemonic legend.
At any time it is possible to leave the actual data entry procedure to return to the main menu (level 0), by pressing the SSMK marked 'COMM RST'.

MECHANICAL DESIGN

The equipment is fitted on and forms the upper part of the cockpit.
Its external profile defines the maximum viewing angle of the pilot and costitutes the cover for the cockpit with anti-glare function while at the bottom the shape is limited by the shape of other equipments.
The GLARE SHIELDS are Line Replaceable Units, fixed on the aircraft structure by bolts and hinged to the central create in order to swing and to allow replacement of other cockpit equipment without requiring their disassembly.
The front shape of the units looks like two triangles joined at a corner, and the left unit is approximately the mirror image of the right unit.
On both units the upper part contains the power supply module, a front panel and the main connectors on the rear while the lower part contains the electronic modules and another front panel.
The two front panels of LHGS carry push-button matrix with programmable legends: on the upper panel are located the System/Sub-system Moding Keys (SSMK) and on the lower panel are located the Data Entry Keys (DEK).
The mechanical design was carried out also taking into the account maintainability aspects.
The electronic circuitry is splitted into three plug-in cards connected together by means of a motherboard and front panels are interfaced with the wiring harness by means of connectors in order to allow their replacement without removing the GLARE SHIELDS from the aircraft.
The plug-in cards and motherboard are supported by a metal frame with fins on the external side and guides for cards on the opposite side.
On the bottom surface of the upper part of the case a flood light is installed for night flight. The flood l[illegible] is a custom electroluminescent device plug-in mounted with a thickness of 2 mil[illegible]ters.
The metal structure of the case is obtained by aluminium alloy investment casting. This technology was selected because is allows to realize the complicate shape, due to the installation requirements, leaving the maximum possible internal space and furthermore it assures the necessary strenght in the critical area: the joining point between the triangles. The material used for the casting assures also a good thermal dissipation and reduces manufacturing time and cost.
Each case after casting process is checked with penetrant fluid and x-rays to prevent cracks and the dimensions are controlled to guarantee mechanical tolerances.
The GLARE SHIELDS do not require forced air ventilation.
The thermal management of the GLARE SHIELD is performed by conducting the heat flow to the main frame of the equipment.
The main areas of heat generation are localized on the electronic modules, power supply

and displays.
The thermal dissipation of the electronic modules is assured by means of heat sink bonded on PCBs joined to the finned metal frame by metal clamps, the power supply layout is designed to have the high power devices placed on a large finned plate to form an external wall of the unit and the LED displays dissipation is carried out by means of heatsink and front panel surface.

PROGRAMMABLE PUSH-BUTTON DESIGN

Many features of the MDEF are achieved by using a new developed push-button assembly that combines the typing performances of a true push-button with the flexibility of a LED display used for the legend.
Design problems were mainly in the combination of these two requirements that have impact on the mechanical design of the push-button by minimizing the size, the number of moving parts and the thermal management of the item.
Fig. 6 shows an exploded view of the legend programmable push-button.
It consists of a miniature switch module containing the momentary single pole contact and the mechanical parts to provide the correct actuation travel and force.
The moving part of the switch is shaped as two fins providing the interface with the front cap of the push-button and are designed to pass through the printed circuit board, by the side of the display package to the filter acting as a contrast enhancer media and moving cap. The multilayer PCB connects the switches and the display packages to the electronic modules and acts also as a mechanical support for the switch module on the back and the LED display package and the relevant heat sink on the top.
The front panel covers the switch assembly, acts as a guide and retainer for the filter and provides the mechanical separation between switches.
The displays selected to realize the programmable legend in the push-button assembly are a sunlight readable version of the high performance green four characters 5 by 7 dot matrix alphanumeric display HP-2303.
Each four character cluster is contained in a 12 pin dual-in-line package with front glass window.
The light emitting diode array produces an alphanumeric character 5 millimeters high and is driven by an on-chip serial input/parallel output shift register and associated constant current LED driver.
This feature allows an easy interface between display chips by connecting the shift registers in serial mode and driving the character array with the clock, the serial signal and the decoded column number.
The peak wavelength of the LED array is 570 nanometers, falling in the greenish-yellow region of the CIE Standard Observer Curve.
This wavelength has been selected because the emission of the LED in the region in which the night vision goggle are sensitive is very low (at 645 nm. the emission is about three hundred times lower than at 570 nm.) and a complete night vision goggle compatibility can be easly acheived by using of filters.

ELECTRONIC DESIGN

The electronic circuitry of the GLARE SHIELDS is organized in four replaceable modules connected together through a common motherboard (fig. 7).
They are:

- Processor Module
- Keyboard and Display Driver Card
- 1553 Remote Terminal Card
- Display Power Driver Card

The processor module contains all the circuitry related to the computing facilities implemented in the GLARE SHIELDS.
It is designed around a Z8002 16 bit microprocessor running at 6 MHz of clock speed with program and data memory realized with an hybrid circuit containing EPROM and RAM.
To support real time processing four programmable counters are available also used to generate master synchronism for the display controller module.
The processor module contains also circuitry to access to the other cards as pheripherals

via a buffered address, data and control lines and facilities to support both continuous and interruptive built-in test.
The display controller module generates all the timing required to drive the LED displays and to scan the switches matrix. The processor can access the display controller as a peripheral to read status informations and keyboard data.
The controller is organized as a state machine that in sequence reads from a dedicated memroy the data to be displayed, serializes and sends them with the clock to the appropriate display array. To avoid flickerring, the displays are organized in four indipendent serial arrays of eleven displays each connected with common columns lines.
The data to be serialized are collected from the display data memory that can also be accessed by the processor and is software organized in dedicated locations for each display with data already converted with the appropriate font from ASCII code to the display format ready to be serialized.
The module contains also the circuit to control the brightness of the LED array by receiving the centralized brightness control signals and converting them into variations of the width of the column pulses that are generated by the display controller card and buffered by the display power driver card.
In a separate module a complete 1553B dual redundant Remote Terminal Unit is implemented with the adoption of an hybrid circuit that integrate the functions of protocol controller, serial transmitter and receiver and line amplifiers. Data words received and transmitted are placed in a dedicated memory area in the processor board and are transferred to the 1553 module in DMA mode. Mode codes and subaddress data field are also supported. The error conditions are handled by the processor advised with dedicated interrupt lines and status words.
The switching mode power supply generates from a 115 Volts 400 Hertz input the voltages to be used in the different modules: 5 VDC for the logic circuitry, the positive and negative 15 VDC for the 1553 interfaces and the 5 VDC high current output for the display array.

CONCLUSIONS

The GLARE SHIELDS were successfully tested during the flight trials of the EAP prototype. Reports from the pilots gave us the confidence that the main design goal was fulfilled by confirming the improvement of the operational capabilities of the cockpit.
The Avionics System and Equipment Group of Aeritalia is also carrying out design activities in order to meet new requirements and to increase the operational capabilities of this category of equipment with the use of new technologies as Liquid Cristal Displays in replacement of the LED displays.
Despite their problems to the extreme temperature range, LCD offers a favourable [illegible] in terms of thermal dissipation, reliability and circuit complexity with better operational capabilities due to the easy customization of such devices in terms of graphic presentation.

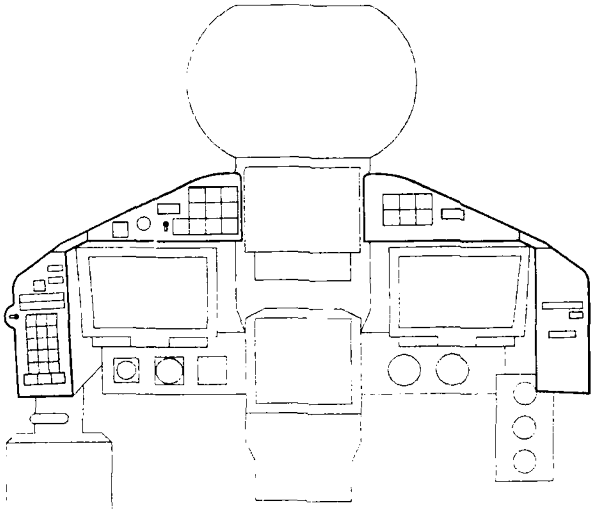

Fig. 1 GLARE SHIELDS COCKPIT INSTALLATION

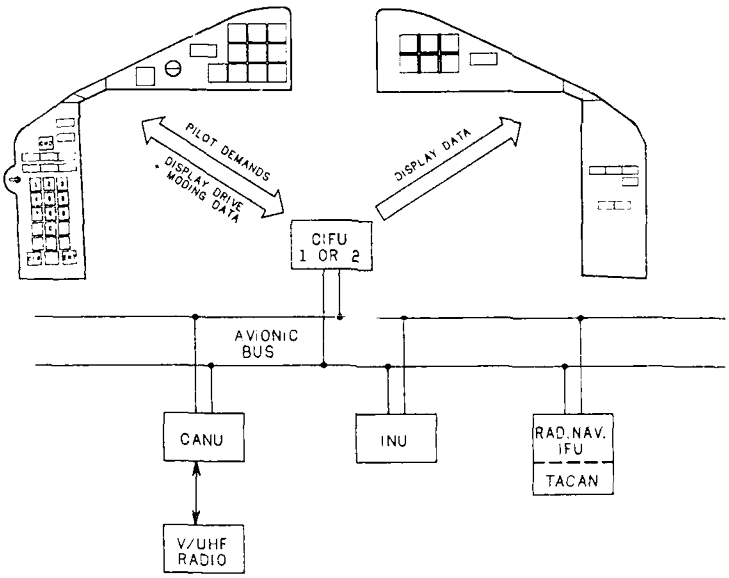

Fig. 2 SYSTEM BLOCK DIAGRAM

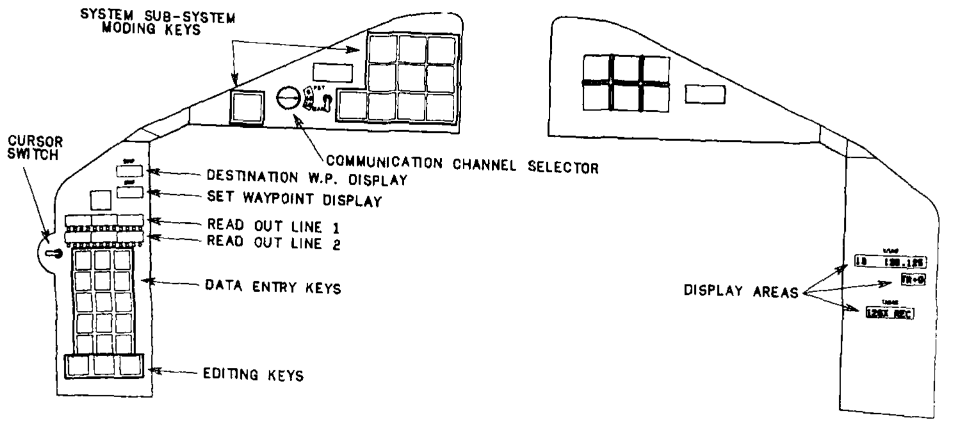

Fig. 3 LH AND RH GLARE SHIELDS

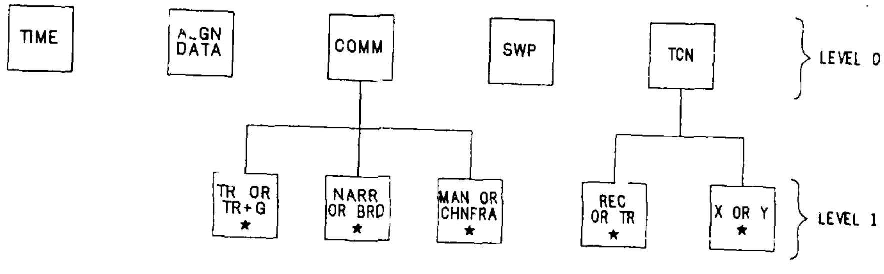

Fig. 4 MDEF LEVELS ORGANIZATION

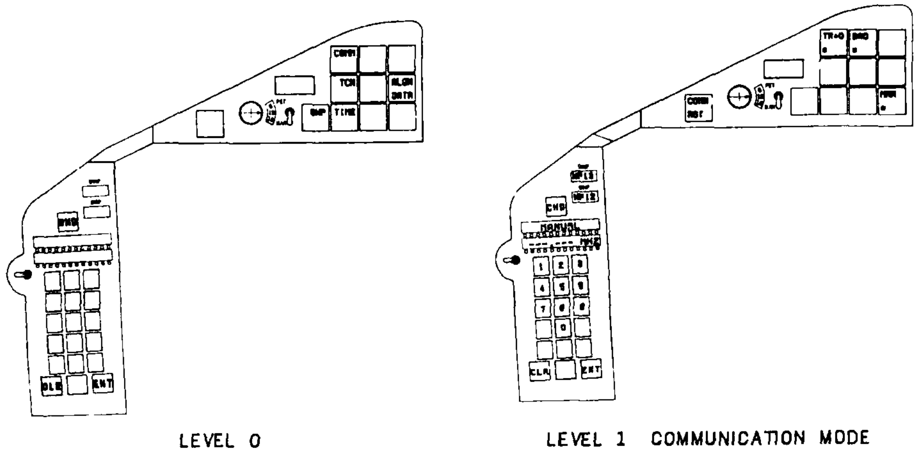

Fig. 5 SSMK CONFIGURATION

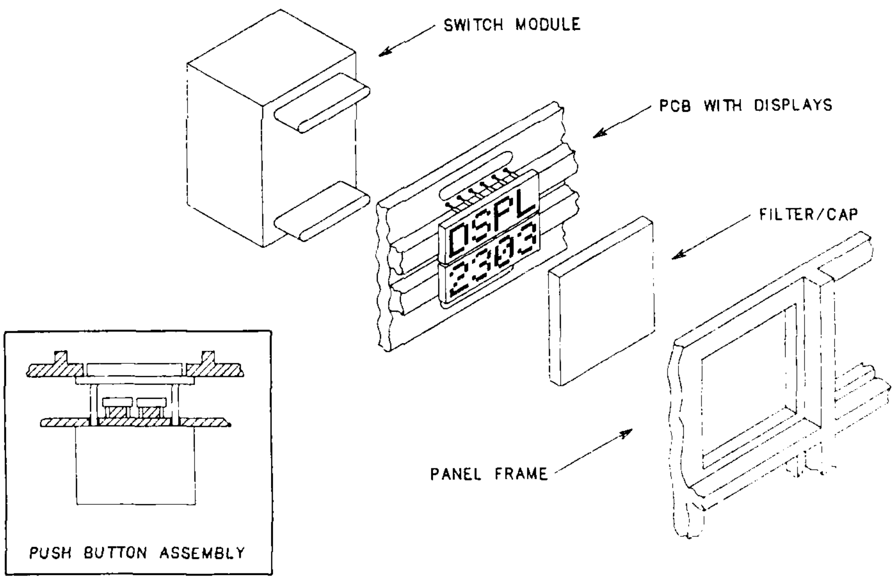

Fig. 6 PUSH BUTTON EXPLODED VIEW

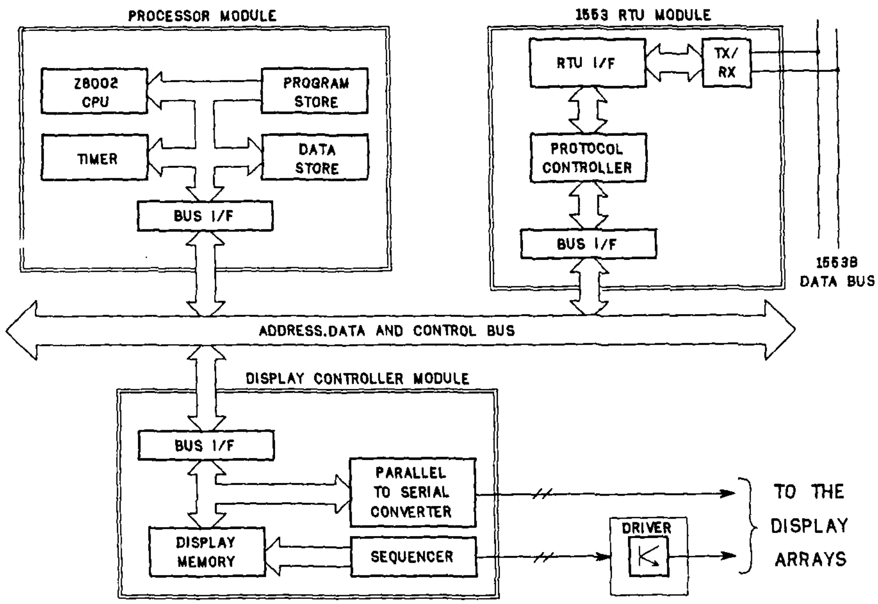

Fig. 7 ELECTRONIC MODULE BLOCK DIAGRAM

PANORAMIC COCKPIT CONTROL AND DISPLAY SYSTEM (PCCADS)

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SUMMARY A real-time, pilot interactive demonstration and test of a large area fighter cockpit display has been conducted. The test of this large area (38cm X 51cm), full color display was conducted in a mock-up cockpit at the McDonnell Aircraft simulation facility. This display used essentially the entire instrument panel area to present a moving map with symbology and other information overlain and also presented sensor imagery and other information as required. The information presented could be customized for a particular mission phase or other need. A touch sensitive display as well as other advanced control concepts were also demonstrated in conjunction with the large area display. This display and control concept simplifies and automates many of the control and display functions for the pilot of an advanced fighter aircraft. The results of demonstration and testing with ten pilots will be presented.

INTRODUCTION

Poor "situation awareness" is the area cited by aircrews as the primary deficiency of present day fighter aircraft. The information that the aircrews need to know is: (1) their location; (2) the location, type and capability of the friendly forces; (3) the location, type and capability of the targets and (4) the location of all threats and their associated lethality. Moreover, we feel this information needs to be fused, integrated and controllable in a single color display for easy understanding. Most of the above information is presented in todays aircraft, in various display formats and to various scales, on discrete displays located throughout the cockpit. The crew must mentally fuse these various sources of information to obtain a picture of the total situation.

A number of new display concepts aimed at improving situation awareness and simplifying the aircrew tasks can only be implemented properly using a larger, more flexible and controllable color display area. In this context, "large area" is meant to imply a display area of at least 1200 sq. centimeters viewing area. Flight-worthy color display technology does not exist, neither direct view or projection, flat panels or cathode ray tubes (CRT), to provide such a large area cockpit display in high brightness, high resolution, and full color. However, existing display technology is adequate to build a cockpit simulator (ground based) version of PCCADS, where packaging, volume, and environmental limitations are less constraining.

The PCCADS program evaluated (with ground based equipment) the benefits of a large area color display and advanced control concepts which are unconstrained by the information placement and formatting afforded by today's small area cockpit CRT displays. This PCCADS evaluation is the first step in pursuit of the cockpit technology which will replace today's limited capability by a large area display having flexible formatting and information placement capability. PCCADS allows custom formatting of displays to provide the most appropriate use of the instrument panel surface during each mission segment. Advanced PCCADS touch panel, helmet mounted sight and voice control devices were used along with the PCCADS large area color display to demonstrate a simplification of the pilot's task and provide a more effective pilot/aircraft interface and weapon system.

BACKGROUND: In recent years, fighter aircraft and missions have been growing more complex and difficult. for the past two decades the growing problem of system control has been approached by simply adding displays and controls to the crew station. This process has continued to the point where the large number of controls has very nearly become unmanageable by the aircrew. Simultaneously, display area for sensors has decreased. For instance, the F-111A (1960) radar has an 18 centimeter diameter radar display. The F-16A (1980) now has a 10 centimeter square radar display which must be shared with control functions. In essence, multi-million dollar sensors are now being interfaced with the aircrew through miniature, time shared displays. This problem is now being addressed by creative thinking, less constrained by existing technology, and by a consideration of both the information displayed and the control techniques in relation to the capabilities of the pilot. Prior to the PCCADS program a study entitled "Display Techniques for Advanced Crew Stations" was completed. The study explored advanced control and display techniques and their effect on future fighter/attack aircraft crew stations. The emphasis was on new and developing technology with innovative applications to integrated avionics systems. The study reviewed anticipated future mission requirements, established display requirements and reviewed display technologies as well as information placement, formatting and use.

SITUATION AWARENESS

To be successful in air combat, the tactical fighter pilot must establish situation awareness at the start of each mission, then maintain it throughout the mission. Pilots continually state the importance of situation awareness, and recent studies indicate it is the decisive factor in determining the victor in air combat. Defining "situation awareness" is not simple. This study has chosen to adopt the Tactical Air Command definition as set forth in the final report of the Intraflight Command Control, and Communications Symposium. It states that situation awareness consists of the following elements:

(1) Knowing where the friendlies are and what they are doing.

(2) Knowing where the threats are and what they are doing.

(3) Knowing what my flight knows and what our options are for offense/defense.

(4) Knowing what other flights know and what their intentions are.

(5) Knowing what part of the above is not known or is missing.

Current cockpit display systems present problems in gaining and maintaining situation awareness. This is because of the evolution of fighter aircraft from simple aircraft with guns mounted on them to jet aircraft possessing an airborne radar system, and ultimately, to the present generation of advanced fighters containing a multitude of sensors for detecting both ground and air targets, detecting threats, navigating and maintaining communication with other aircraft and command and control elements. The systems which make use of these sensors have been added to fighter aircraft one at a time. Each has brought to the aircraft its own display formats and, in many cases, its own dedicated display system. As a result of this evolution, present day fighter cockpits often provide the situation to the pilot by means of several different, often dedicated, displays. Each of these displays provides the data obtained from one type of sensor. Each of these displays uses its own unique format, and often each is set to a different range scale. The pilot is faced with the problem of mentally fusing the data provided by these different displays into a single mental picture of the tactical situation. Because it takes time to do this, gaining situation awareness is difficult; maintaining it in the "heat of battle" is nearly impossible.

A sample fusion problem is shown in Figure 1. Radar information, displayed on a B-scope, must be interpreted, then correlated with the data from navigation (NAV), electronic warfare (EW), and Joint Tactical Information Distribution System (JTIDS)

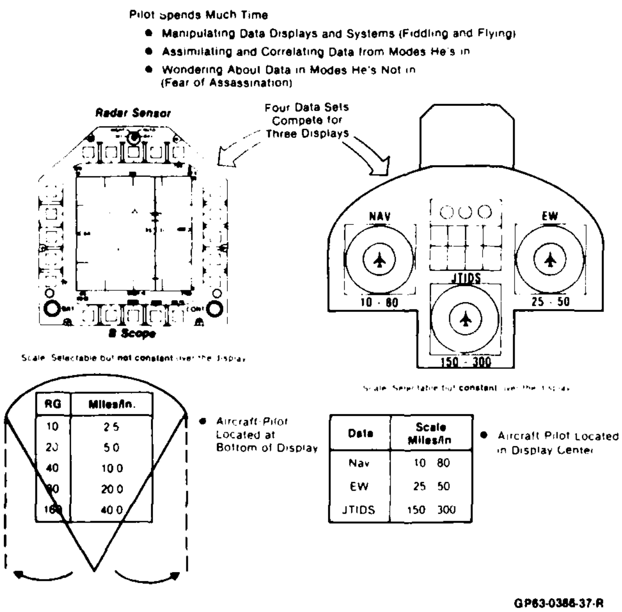

Figure 1. Example Information Fusion Problem

displays. At a minimum, the B-scope radar format will differ from the other three, which normally employ a 360 degree planform format. Normally, each of the four displays will be set to different range scales. This problem is further complicated by the fact that some targets will show up on all displays, occupying slightly different positions as a result of the different formats in use. These must be recognized as being different depictions of a single physical object. Conversely, some items may show up on only one display, and must be recognized as unique elements of the situation. Thus, as part of the overall fusion problem, the pilot must determine similarities and differences in the various displays in order to accurately assess the situation. As technological advances continue, these problems will continue to grow in magnitude.

PCCADS/BIG PICTURE SOLUTION

One solution to this problem is to integrate the available data and then provide all information relevant to the situation on a single display. However, the display must be large enough to display this data without becoming to cluttered. Currently, cockpit CRT displays provide only 150 - 250 sq. centimeters of display surface. If radar, JTIDS, EW, and NAV data are all displayed simultaneously in this small area, the resulting display will be too cluttered in all but the most simple situations. To present a complex situation without excessive clutter, the overall display area must be increased.

The main goal of this study was to evaluate the improvements to situation awareness that could be obtained by the use of a single, large area, color display. A single display is required to fuse all sensor data into a single picture of the tactical situation, with all elements plotted on a single format and using the same scale. A large scale is required to handle the clutter problem; consequently, a display area of 1900 sq. centimeters was employed, and the display occupied essentially the entire instrument panel of the cockpit. Finally color was used to encode some of the information, so that certain aspects of the situation could be seen at a glance by the pilot (e.g. hostile vs. friendly aircraft).

Another aspect of the problem to be investigated was pilot interaction with the aircraft. As pointed out previously, the pilot must presently expend a great deal of time and effort in direct control and coordination of on-board sensor modes and displays. Several improvements are possible in this area. First, to accomplish a certain task, all onboard sensors are simultaneously directed to obtain the necessary information. Second, several aspects of sensor control can be automated to that selection of an operating mode for the system will automatically place all sensors in the optimum modes and parameters for the task at hand. While override modes may be required to handle special situations, the more common situations can be automated so that less pilot effort is required. This frees the pilot to concentrate on tactics instead of sensor selection and operation.

Unfortunately the display technology does not currently exist to provide a large area display with sufficient brightness and resolution in an acutal aircraft. However, a large area display with sufficient brightness and resolution could be provided in a simulator to demonstrate and test the value of such a display. In addition to the large display and the integration and automation of sensor operation mentioned above, we wished to demonstrate the value of advanced control concepts such as HOTAS (Hands on Throttle and Stick), Touch Panel, Automatic Speech Recognition, and an HMS (Helmet Mounted Sight). The HOTAS control approach allows the pilot to control various functions and subsystems without removing his hands from the stick or throttle. The pilot is able to perform various control operations by using either dedicated switches or controls on the stick and throttles, or by controlling a cursor on the display to select options present on a particular display format. The touch panel uses an overlay grid of infrared beams which are interrupted at a particular location when the pilot touches the display. Using this touch control he can designate items on the display, make selections from menu items, draw routes and move inset displays. Voice control is used either alone to perform various operations or in conjunction with touch control. The use of voice and touch simultaneously allows the pilot to designate an item with touch and then with voice have the system perform some action on the display item designated. The helmet mounted sight may be used similar to touch to designate an item on the display or to control a cursor on the display.

PCCADS SIMULATOR

The display in the simulator cockpit is a 38 X 50 centimeter rear projection screen. Two video projectors were used to project onto the screen. One projector provided the background display which was usually a moving map, while the other projector provided all of the overlay information which included ownship position, friendly positions, positions of other aircraft, threat locations, target locations, route-of-flight, and other information as required to perform various mission tasks. Insets in the display formats could also be provided. These insets included radar and FLIR imagery and graphic insets such as weapon status and fuel status depicted in pictorial format. The insets are always available, but they are only displayed when the pilot selects them. Once displayed they can be enlarged, reduced, moved to any location on the display, or completely removed from the display. The intent is that they are used only as needed by the pilot to provide additional information. Figures 2 to 5 show typical display formats which are in color in the actual simulator.

A graphics system was designed to generate the required display elements. Key components are the MIGS (Map Image Generation System), the Compuscene, an IRIS, a Graphics Processor, and a projection system. A functional block diagram depicting the

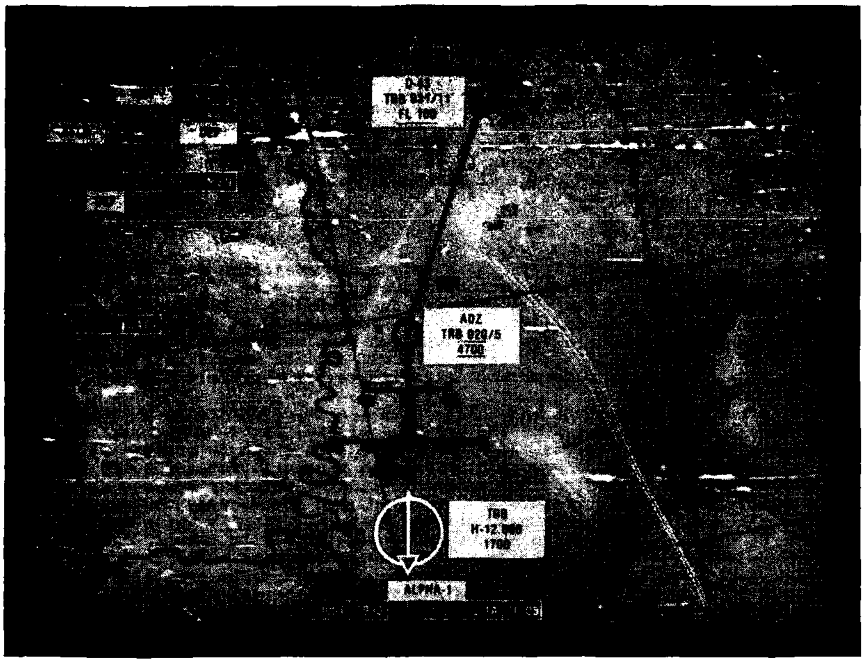

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Figure 2. Departure Format

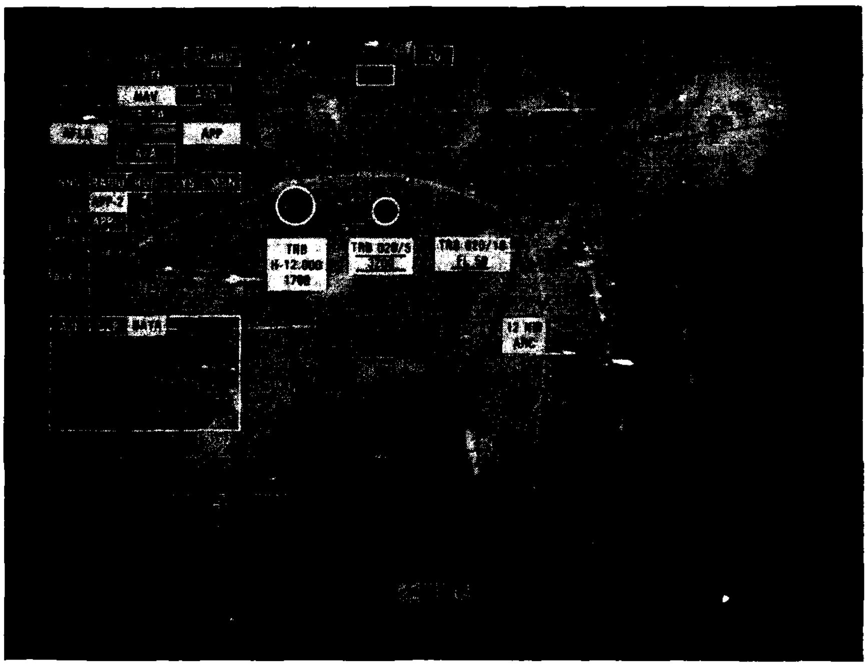

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Figure 3. Approach Format

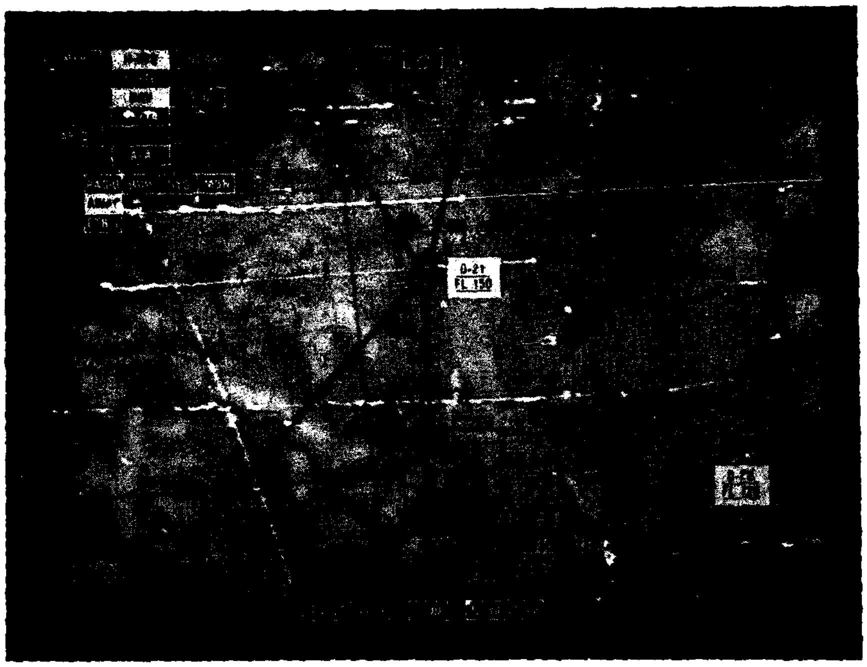

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Figure 4. High/Low Routes Format

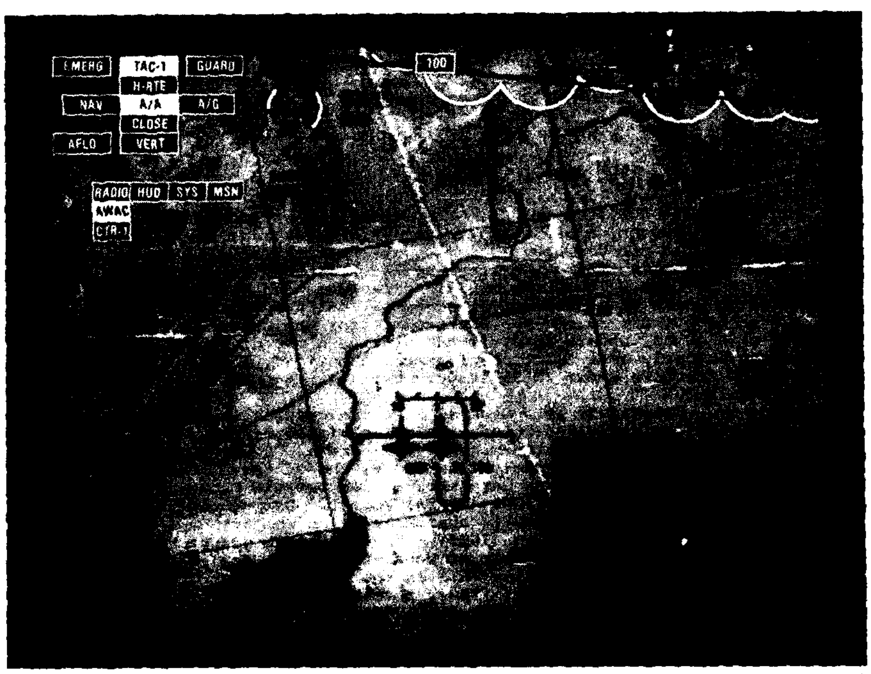

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Figure 5. Tactical-1 Format

entire system is shown in Figure 6 and key components are described in the following paragraphs.

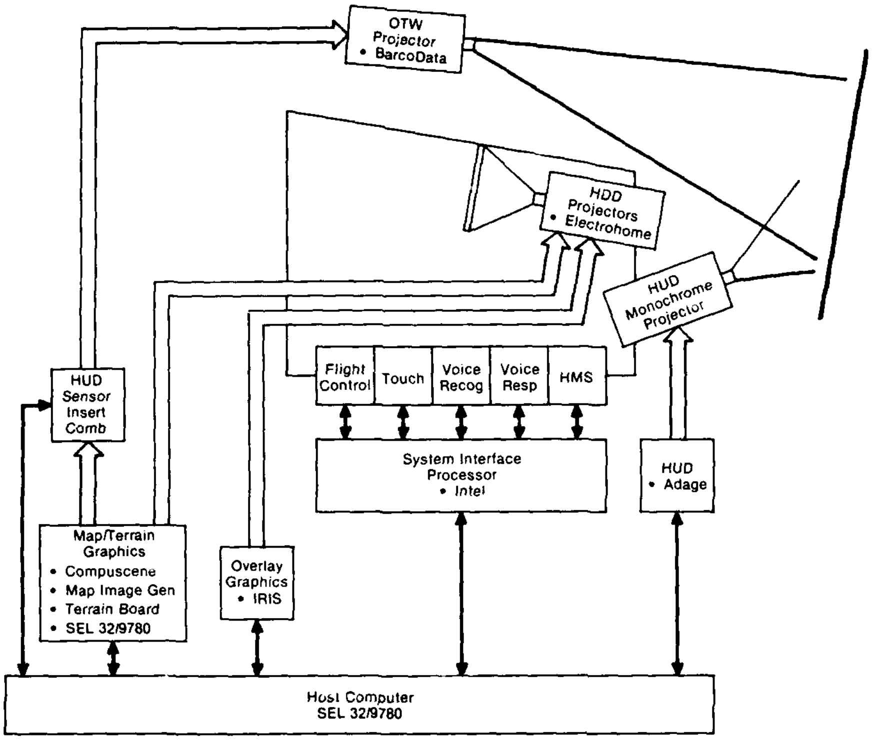

Figure 6. PCCADS Simulator

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Map Image Generation System (MIGS) - The MIGS is a McAir developed system that combines an Image Processor, a 300 megabyte real-time disk, and special image generation circuitry to produce digital maps. The "real-time disk" is a magnetic, fixed disk that is capable of transferring the 256 kilobytes required to form one frame of video in 33 msec. Thus, the MIGS is capable of supporting a 30 hz. video frame update rate, which gives the appearance of a continuous, real-time video image. The MIGS is used to provide moving map backgrounds for the head-down display. Since it is capable of a 30 hz. update rate, it can provide a map display that moves smoothly and continuously as a function of aircraft motion. The MIGS is also used to provide Synthetic Aperture Radar (SAR) imagery by inserting prestored SAR frames into the map when required.

Compuscene IV - Compuscene is a General Electric graphics system that is used primarily to provide digitally generated, realistic visual displays. This system is used primarily to provide the out-the-window (OTW) scene. However, Compuscene can provide up to four independent channels; therefore, one of these channels is used by the head down display to provide the perspective view terrain background employed by the terrain following/terrain avoidance (TF/TA) format. Compuscene is also used to provide simulated FLIR imagery, which is available as an inset.

Integrated Raster Imaging System (IRIS) - The IRIS is a graphics engine produced by Silicon Graphics Inc. that is capable of zoom, rotations, scalings, perspective views, etc. The primary purpose of the IRIS is the production of overlay graphics; i.e. aircraft symbols, route of flight lines, threat rings, etc. The IRIS is also used to produce many of the pictorial format inserts that are employed.

PROJECTION SYSTEM

The HDD projection system, including the two projectors, is physically located in the "nose" of the PCCADS cockpit shell. This is shown in Figure 7. All other elements of the HDD graphics system are physically remote from the cockpit.

The HUD is a projected display, the PCCADS crew station only simulates a HUD.

Since the PCCADS cockpit will only be used as an evaluation tool, it was decided to project the HUD displays on the OTW scene. This has the advantage of allowing all individuals present to view the HUD display, as opposed to an actual HUD that can only be seen by the cockpit occupant.

OTW Projection for the main PCCADS testing was performed in a 12 meter diameter dome. This provides a full 360 degree visual display. Compuscene is used to produce half of the visual scene, which is projected onto the forward inside surface of the dome, the remaining portion is produced by a dynamic earth/sky system which projects simple low resolution imagery on the remainder of the dome.

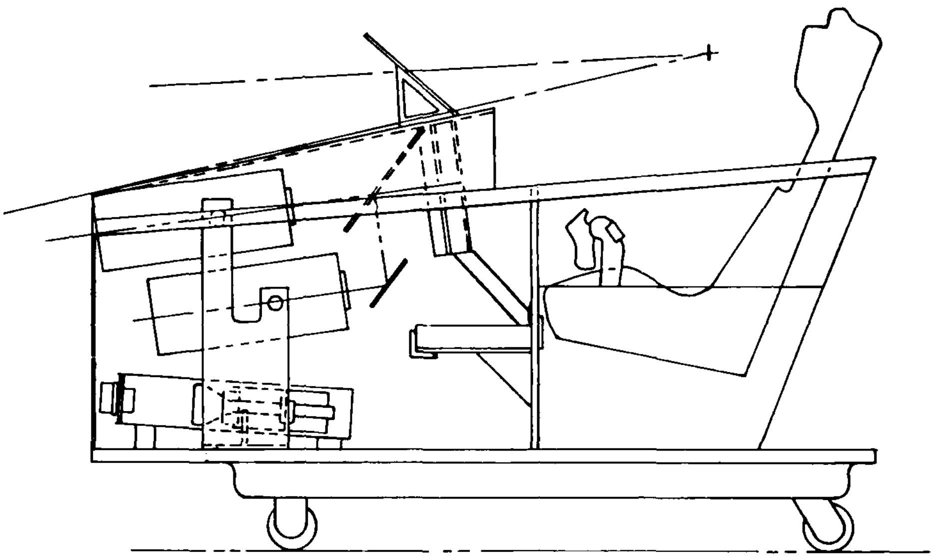

Figure 7. PCCADS Projection System

PCCADS EVALUATION

The PCCADS crew station was evaluated in both air-to-air and air-to-ground full mission piloted simulation.

Each pilot flew both the air-to-air scenario and air-to-ground scenario once. Each scenario was divided into segments for the purpose of data collection.

The air-to-air scenario was a defensive counter-air mission. As part of the Blue Force, the participating pilots had the mission of defending Blue airfields from attacking Red bombers and accompanying fighters. An overall view of the air-to-air scenario is shown in Figure 8. The defending Blue fighter encountered two waves of four ingressing Red fighters. It was required to defeat both waves and return to base within fuel and weapons load limitations.

The air-to-ground scenario was an air-to-ground interdiction mission as depicted in Figure 9. The participating pilot was lead in a two ship flight directed to strike an armored column behind the FEBA using infrared guided missiles. A second strike employed CBU weapons against personnel carriers designated by a laser-spot tracker. Both surface and air threats were encountered during the mission. Mission replanning was required during ingress to minimize threat and maintain time-on-target. Air threats and a fuel emergency were encountered after the second strike.

PROCEDURES

The PCCADS crew station was evaluated in 80 hours of piloted simulation including all major phases of air-to-air and air-to-ground missions. Extensive training consisting of eight hours of "ground school" academic training and six hours of hands-on familiarization was given to all participants. The eighty hours of simulation were divided between 40 hours of simulation in a domed facility with a complete 360 degree out-the-window scene and 40 hours of simulation with a 40 degree out-of-the window scene (see Figure 10). Air Force pilots participated only in the domed facility. Performance data were collected in real-time by the PCCADS computer system. Missions were divided into a series of initial conditions at significant points. Subjective situation awareness and workload data were collected by questionnaire during breaks between initial conditions.

PILOTS

Ten pilots were employed in the evaluation. Six of these were McAir pilots with previous operational fighter experience. Each of the four pilots supplied by TAC also were previous or current fighter pilots. The total group encompassed more than 5,000 hours of experience in F-15, F-4, F-111, F-100, and F-106 aircraft. All pilots participated in all phases of both the air-to-air and air-to-ground missions at least once.

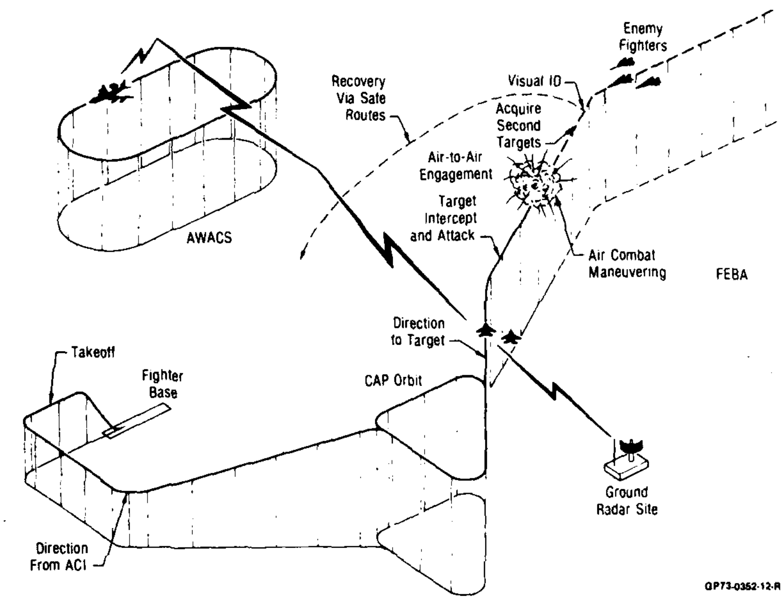

Figure 8. Air-to-Air Mission Segments

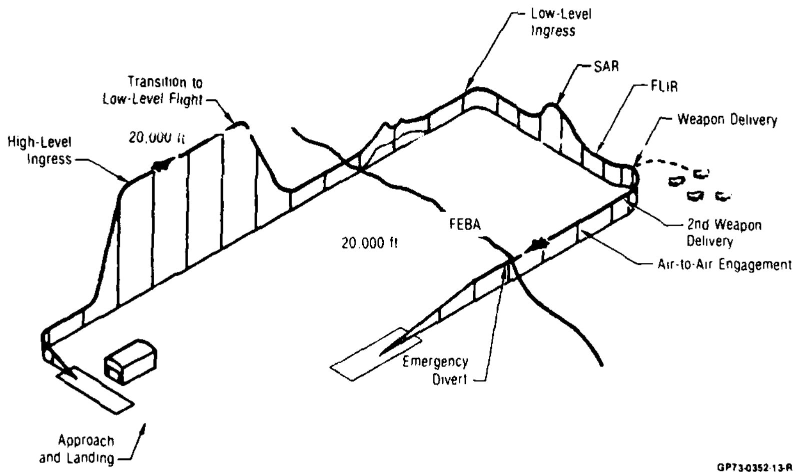

Figure 9. Air-to-Ground Mission Segments

FIGURE 10

RESULTS

Performance data and subjective workload data and situation awareness data were collected during testing in both the stall and the dome. At this writing only the subjective data from the stall testing has been analyzed. A situation awareness measure devised for evaluation and the Subjective Workload Assessment Technique (SWAT) were used. The situation awareness scale, shown in Figure 11, was based on the definition of situation awareness given at a symposium sponsored by the 57th Fighter Weapons Wing. The preliminary results shown in Figure 12, indicate the missions were performed with high levels of situation awareness and moderate levels of workload.

	COMPLETELY DISAGREE						COMPLETELY AGREE
1. I always knew where the friendly forces were and what they were doing.	1	2	3	4	5	6	7
2. The positions and actions of threat forces were always determined easily and without effort.	1	2	3	4	5	6	7
3. I was always aware of my own options.	1	2	3	4	5	6	7
4. The status of my own aircraft could always be determined easily.	1	2	3	4	5	6	7
5. I could easily determine the position of my own aircraft.	1	2	3	4	5	6	7
6. It was easy to realize when important information was missing or inconsistent.	1	2	3	4	5	6	7

1. "position" includes heading, speed, attitude and relationship to the ground.
2. "forces" means all forces air/ground.
3. "status" refers to internal conditions of the aircraft fuel, sensor availability, etc.

Figure 11. The Situation Awareness Scale

SEGMENT	FRIENDLY FORCES	THREAT FORCES	OWN OPTIONS	OWN AIRCRAFT	OWN POSITION	INFORMATION QUALITY	WORKLOAD
AIR-TO-AIR							
TAKEOFF	4.3	3.7	5.0	4.7	5.5	6.0	18
SCI TO CAP	5.2	4.7	5.2	5.7	5.7	5.2	19
INTERCEPT ONE	5.5	6.2	5.7	5.5	5.7	5.3	48
INTERCEPT TWO	5.8	6.5	5.3	6.0	5.5	4.8	42
C3 TO TARGET	5.8	5.5	5.7	5.8	5.5	5.3	44
VISUAL ID	4.5	4.7	5.3	5.7	5.8	4.5	52
APPROACH	6.0	5.7	5.3	5.7	5.8	5.3	62
AIR-TO-GROUND							
DEPARTURE	6.0	5.5	5.5	5.2	6.0	5.0	16
HIGH INGRESS	5.5	5.8	4.7	5.3	5.2	5.0	36
DESCENT	5.8	5.7	5.3	5.3	5.7	5.3	34
LOW-INGRESS	5.7	5.8	5.0	5.2	5.3	4.6	61
SAR	5.5	5.5	4.7	4.3	5.5	4.2	69
FLIR	5.5	5.7	4.5	4.8	5.5	4.0	81
DELIVERY ONE	5.8	5.7	4.8	4.7	5.2	4.2	82
DELIVERY TWO	5.5	5.5	4.8	4.7	5.3	4.5	77
AIR ENGAGEMENT	5.8	5.0	5.5	5.3	6.3	4.3	79
EMERGENCY	6.2	6.2	5.0	4.8	5.3	4.5	57

Figure 12. Mean Situation Awareness and Workload Ratings During Stall Testing

MULTISENSOR TARGET RECONNAISSANCE

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Summary:

An example of the concept of a knowledge based sensor fusion system will be presented, which combines a radar primary sensor with an IR secondary sensor. The radar's wide range of view is used for Target Recognition over a large area, while the IR sensor's high resolution at a small angle of aperture is employed for target classification.

1. Basic considerations

Although much has been done in the field of target fightin, to reduce the exposure time of one's own platform (e.g. Third Generations-, Fire & Forget - Missiles), modern target reconnaissance still depends largely on the performance of the human observer, which is, of course, governed to a large extent by the degree of stress felt in the prevailing battlefield situation.

Enhancing combat efficiency and improving the survival rate of friendly weapon systems therefore requires a greater automation and, in consequence, acceleration of the processes of target reconnaissance up to weapon alignment.

Since no single sensor will be available even in the distant future to provide all the required information by itself, it will be necessary to have an aggregate of sensors supplementing and supporting each other by virtue of their specific qualities.

However, it will be a special feature of future sensor systems that not the improvement of individual sensors will enhance scope and efficiency of any weapon system, but the combination of several sensors with powerful methods of Multisensor-Processing.

There are three basic principles to combine sensors in a target-acquisition-system (fig.1):

- the use of several sensors of the same type (monospectral) with the same quality and the same parameters to enlarge the field of view (FOV)
- the use of different sensors with identical FoV's, but in different spectral ranges to enhance the efficiency in detecting and identifying targets even on adverse conditions (bad weather, counter measures, camouflage) and to reduce failure probability by redundancy.
- the combination of a Wide-Field-Of-View (WFOV) and Narrow-Field-Of-View (NFOV) sensor in a hierarchical structure to get the advantages of the first called possibilities:
  - Monitoring a large area by sensors with less resolution but with a great power in detecting (e.g. Radar)
  - Identifying targets by sensors of high resolution (e.g. IR-Camera), but NFOV.
  - Cueing the NFOV-Sensor by the WFOV-Sensor.

This report contains first results of a sensor fusion with this cueing idea.

2. The Sensor-Fusion-Concept

On condition, that the sensor combination has to observe only objects on a plain area, it is possible to transform the pixels of one sensor to the pixels of the other one. By this way it is possible to emphasize certain macro structures in the NFOV-Sensor (here: TV-Camera), e.g. streets, tracks of fields, edges of forests. It is not possible to enhance smaller objects, because the resolution of WFOV-Sensor (here: Radarfrontend) is not good enough to distinguish shapes.

Effectively this condition does not exist. We are forced to detect low flying objects (e.g. helicopters); the countryside never will be a mathematical plain; the radar is ambiguous in the elevation, the reproduction of the perspective sensor is ambiguous, if the ground is unknown. So, this kind of fusion is unusuable, even the needed computer power would be tolerable.

Possible alternatives are:

Mode 1 Generating frames within the NFOV-picture to mark the regions, in which the WFOV-detected targets could be.

Mode 2 Marking the position of NFOV-identified objects in the WFOV-picture to get track of the situation.

Mode 3 Generating a synthetic picture like fig.3, showing the situation like mode 2, combined with clipped windows like mode 1.

Mode 4 Reducing the information of mode 3 to a statement like this:
Target of type Z in position x,y, priority 1

In future systems (e.g.armoured helicopters of the next decade) modes 3 and 4 are needed. Mode 4 is necessary for automation of the target acquisition to the target alignment process.

To reach this goal, a system like fig. 2 is needed. For each sensor we need two control loops. One loop is to control the operating mode of each sensor, e.g. pulse rate, scan center, scan width and height, transmitting power of the radarfrontend or visual line and focal distance of NFOV-Sensor.

The second loop is to adapt the necessary preprocessing algorithms to the actual situation. The resulting informations of all sensors are gathered and interpreted in the knowledge based system, supported by object modelling data bases. The result, a compressed information like mode 4, is sent to displays or to the arms directly.

3. First results

Fig. 3 shows a display in mode 3. The background shows the information of the used radarfrontend. The system is positioned on the top of a tower. The height is about 25 m. The range of the radar scan is about 3500 m. The five displayed windows show the information of the used TV-Camera (NFOV-Sensor).The equivalent areas are marked by circles.

Fig. 4 shows a clipped area of the rough radar-data of fig. 3. We can notice, that the target (marked by the arrow) is alike other echos of chimneys (upper side of the figure), road signs or clutter.

This figure proves the necessity of radar preprocessing. Fig. 5 shows one example. On the left side you see the rough data, on the right side the selected targets after preprocessing.

Fig. 6. shows the picture of the used TV-Camera, equivalent to fig. 4. The marked window (compare mode 3) shows the position of selected target. It is very difficult to detect the target itself without the help of the sketched frame. It is obvious that the hierarchical structure of the WFOV and NVOV-Sensor is very helpful.

To identify the target, look at fig. 7. It shows the enlarged window of fig.6. On the left half you can see about 64 different grey shades and you can identify them as a small bus (in German: Kleinbus). To gain this information automatically, it is necessary to preprocess the NFOV-pictures, too. On the right side, there is an example of an equivalent segmentation process. Only 3 grey shades remained. To identify the remaining pixel-areas as a Kleinbus, it is necessary to extract additional features and to compare them with stored features of object models. This work is in progress and must be discussed later.

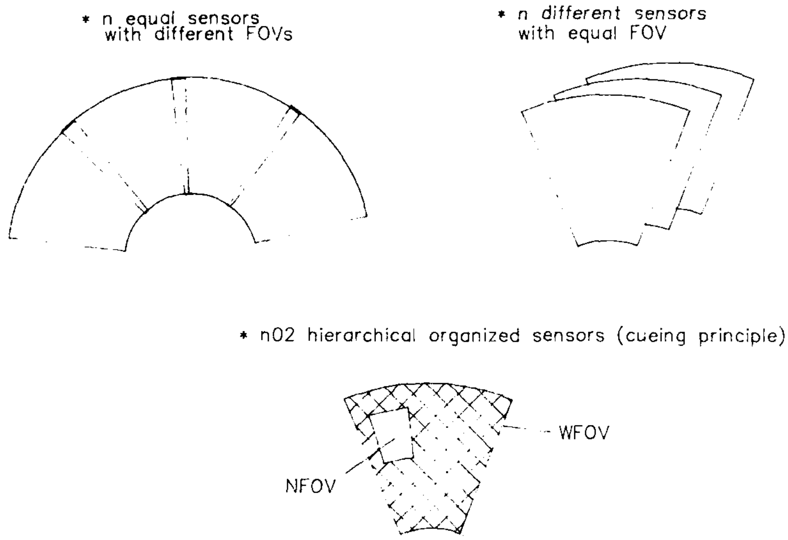

Fig.1 Principles of Sensor Combinations

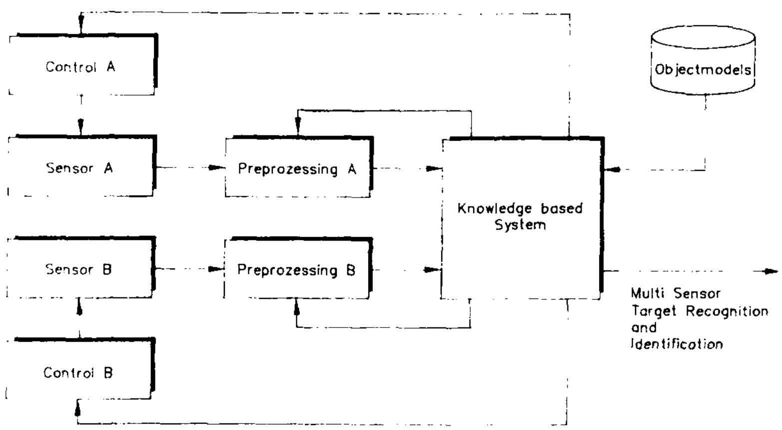

Fig.2 Structure of a hierarchical Sensor-Fusion-System

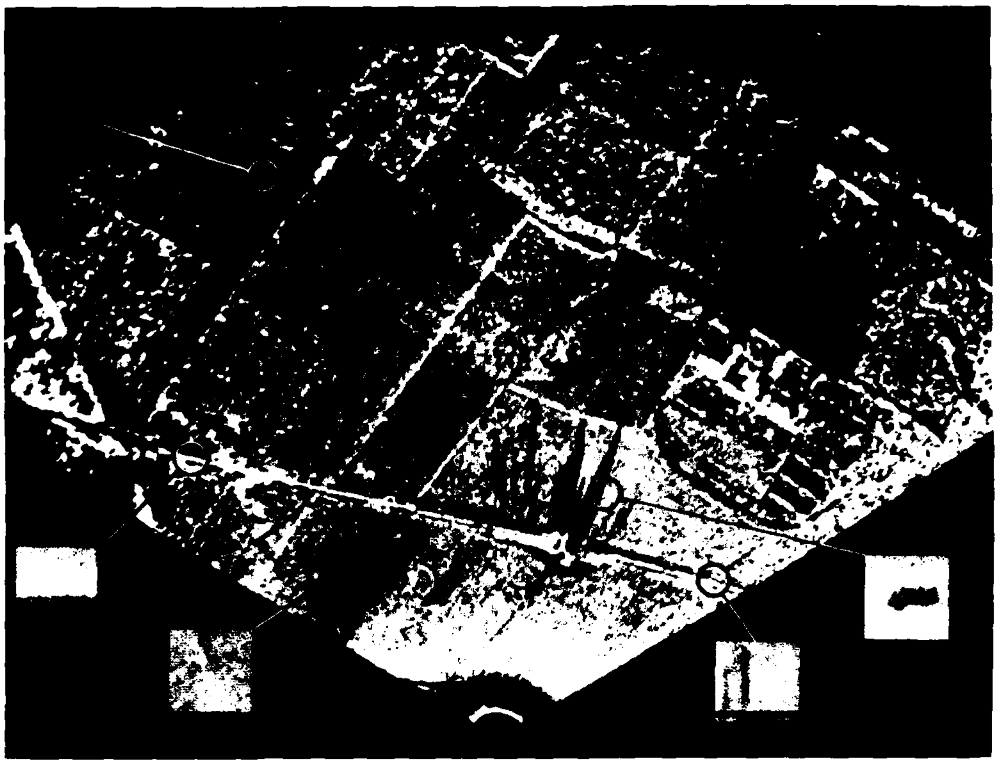

Fig.3 Display in Mode 3

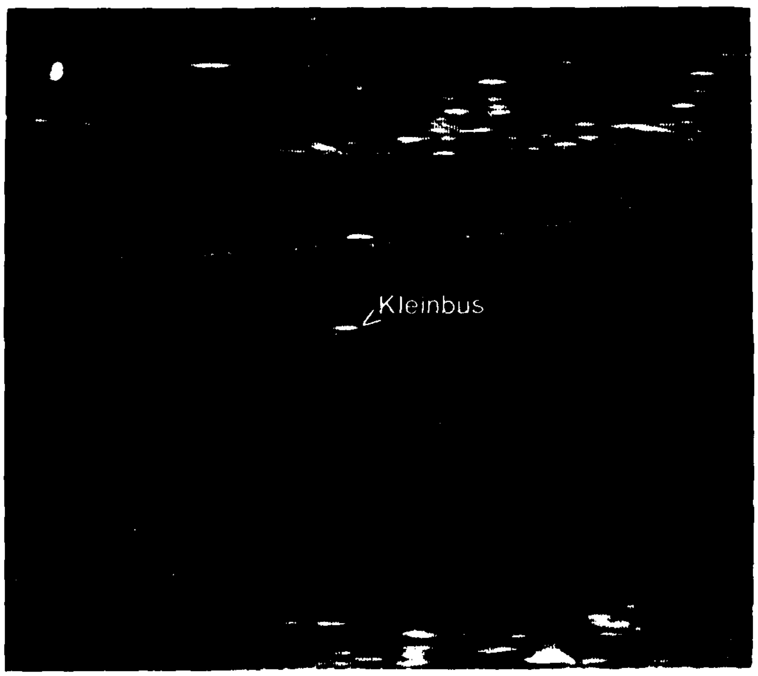

Fig.4 Enlarged Window of WFOV - Sensor

Fig.5
Example of Radar
Preprocessing

Fig.6
The Situation of Fig.4,
shown by the NFOV - Sensor

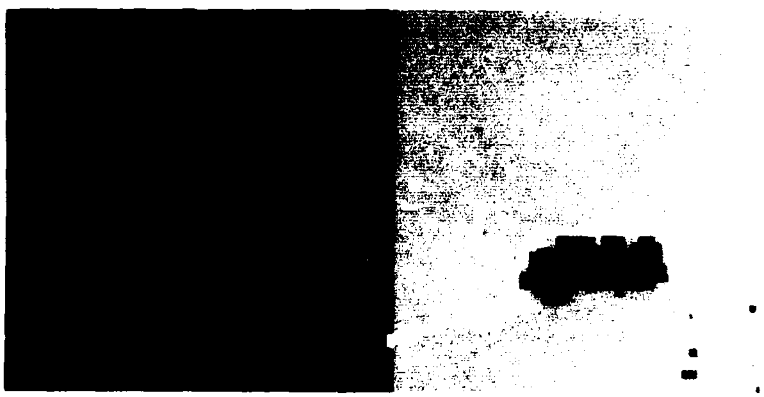

Fig.7
Example of TV
Preprocessing

PILOTES SUPERVISEURS ET GESTIONNAIRES DE SYSTEMES AUTOMATIQUES
UN NOUVEAU ROLE BIEN RISQUE POUR LA FIABILITE DU COUPLE HOMME-MACHINE

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RESUME

Le matériel automatisé, hautement fiable, disponible à bord des avions a fait évoluer le partage des tâches homme-machine. Les observations faites à ce jour et les acquis de la psychologie cognitive démontrent en fait que ce pilote ne supervise pas toute l'activité de la machine mais simplement quelques "noeuds" qui sont des résultats ou des étapes de l'activité où le pilote est directement impliqué. L'opérateur a recentré la représentation de la tâche sur ce qu'il parait être "sa tâche". Ce que fait le système ne figure alors qu'en résumé dans cette même représentation.

Il est notamment démontré à partir d'études réalisées en aviation militaire et civile que la représentation que le pilote s'assigne dans la relation homme-machine est fortement conditionnée par la capacité et la fiabilité qu'il affecte au système. A partir d'un certain seuil de fiabilité conférée au système, le partenaire humain se désengage de la tâche faite par ce système. La représentation de son travail s'appauvrit quant à cette tâche devenue automatisée. Dans ce cas, la capacité de l'opérateur à dépister les erreurs diminue, qu'il s'agisse des erreurs de la machine ou, plus souvent, des erreurs de ce même opérateur au moment ou il a paramétré la machine ou fixé son mode de fonctionnement (et ce du fait du moindre contrôle).

Cet état de fait, brossé grâce à des approches de recherches relevant du champs de la psychologie cognitive, soulève des problèmes très concrets dans la définition des futurs interfaces homme-machine. Plusieurs solutions de réponses sont envisagées en fin de communication.

INTRODUCTION

Sophistication, condensation, électronique informatique, automatismes sont autant de caractéristiques des nouveaux matériels Aéronautiques, particulièrement ceux concernant l'interface homme-machine (H/M).

Extraordinaire terrain des percées des technologies nouvelles, de leurs applications.... l'aéronautique voit se développer des systèmes d'une compléxité et d'une fiabilité impressionnante .

Ainsi, le taux de panne rouge d'un Airbus A310 est réduit à presques zéro sur une année.

Ainsi encore, les centrales à inerties doublées voire triplées pour s'autocontroler, peuvent amener avec une immense fiabilité l'avion à plus de 6000 kms de son point de départ et à moins de 120 mètres d'un point d'arrivée choisi à l'avance.

Un grain de sable peut pourtant apparaître dans cet océan de certitude... c'est celui qui concerne la fiabilité du partenaire humain. L'exemple le plus trivial reste l'équipage qui insère des mauvaises coordonnées du point à atteindre.... Le cas dramatique du Boeing de Korean Air Lines égaré sur le territoire soviétique en est une expression célèbre (**WITKOWSKI,1985**). Le paradoxe est ici que la certitude que développe l'équipage vis à vis de la fiabilité de son système de navigation l'encourage à ne pas vérifier l'évolution de la navigation pourtant de plus en plus aberrante par rapport au but fixé.

Pour plagier un terme aéronautique, il est concevable de dire que l'équipage est dans ce cas "sorti de la boucle". Il ne réalise plus de contrôle de processus, le processus évoluant pour son propre compte.

Ces considérations ne sont pas nouvelles. Elles s'inscrivent dans le cadre d'une véritable transformation de la tâche du pilote (**SANTUCCI et Coll.,1984**).

Le pilote est maintenant devenu un véritable gestionnaire de systèmes complexes. Il touche moins (ou pas du tout) aux commandes de vols et il gère plus les systèmes d'armement et de navigation.

Mais qu'en est-il exactement de cette tâche de gestion? Elle semble ne plus inclure un contrôle de processus minutieux pour chaque système (qui a ce rôle?, ... l'ordinateur de bord?). Elle ne semble pas inclure non plus, et cela est paradoxal, certaines facettes du rôle de superviseur que l'on croit être partie prenante de la tâche du pilote.

Cet article a justement pour but de comprendre un certain nombre d'erreurs en Aéronautique en analysant le modèle mental que développe le pilote chargé en fait d'un contrôle de vol (et uniquement de ce contrôle). *Les inadéquations de ce modèle face aux exigences requises apparaissent comme autant d'explications potentielles des erreurs.*

Notons encore avant de commencer l'analyse que les études classiques sur l'erreur mettent l'accent sur la fiabilité du matériel pour certaines, sur la fiabilité de l'homme pour d'autres.

Une conception désormais classique (symposium OTAN, 1984) considère même l'homme comme le facteur limitant des systèmes d'armes.

Nous voudrions dans cette approche nous positionner de façon paradoxale par rapport aux deux attitudes énoncées en imputant le manque de fiabilité de l'homme à l'excès de fiabilité du système. Cette idée a déjà été évoquée notamment par **WIENER (19185)**. On peut en effet faire l'hypothèse triviale que le modèle mental de l'action développé par l'opérateur est en grande partie dépendant du système sur lequel il travaille et de la connaissance de son système qu'il acquiert progressivement.

L'idée d'un opérateur devenu superviseur n'est pas propre à l'Aéronautique, (voir par exemple **BISSERET, 1984**), mais les conséquences sont particulièrement importantes dans cette branche d'activités.

Pour développer les éléments en faveur d'une telle thèse, nous envisagerons les apports de la littérature dans le domaine du fonctionnement et de l'acquisition de l'expertise dans le contrôle de processus. Des exemples Aéronautiques issus de nos propres travaux illustreront des connaissances édictées souvent dans des domaines autres que l'Aéronautique.

I - FONCTIONNEMENT COGNITIF DANS LE CONTROLE DE PROCESSUS

La tâche de contrôle de processus en pilotage, peut être définie comme le contrôle en temps réel par l'homme d'un déplacement dans l'espace géré par des systèmes (propulsifs ou de guidage). L'homme est capable de corriger, surveiller, éventuellement arrêter l'évolution grace à un certain nombre de commandes et de contrôles.

Les commandes sont, sur les avions actuels, gérées automatiquement par le système (pour une large part) mais le pilote peut surpasser ces automatismes à tous moments et faire manuellement les corrections qu'il souhaite (exemple type : le pilote automatique)

L'ensemble des contrôles (écran de visualisation, cadran divers, etc...) lui fourni un état codé, instantanné du processus - en quelque sorte une représentation du réel - Cette représentation du réel est l'oeuvre du constructeur et des manufacturiers de planches de bord. Elle ne prend pas signification pour le pilote que s'il a appris le codage proposé.

Longtemps stable, ce codage a évolué rapidement ces dernières années du fait des possibilités de l'électronique et des afficheurs. Les informations de synthèse (synthèse de plusieurs autres informations) sont maintenant affichées et animées en temps réel. Elles sont censées économiser à l'opérateur le travail qu'il devait jusque là réaliser lui-même pour développer un jugement. En ce sens leur apparition a fait se déplacer la frontière du partage des tâches H/M. Au-delà du sens, de la signification de l'information, la forme d'affichage a également évoluée : l'analogique a envahi les écrans. Par exemple c'est un dessin de piste qui se projette sur le parebrise lors de l'atterrissage et qui se superpose à la piste réelle (système Persepolis et dérivés). Là encore, il s'agit de faire réaliser par le système une partie du traitement mental que l'opérateur réalisait auparavant pour obtenir un résultat similaire.

Des systèmes encore plus sophistiqués aident l'opérateur dans le diagnostic et le traitement des pannes. Dans certaines situations, ces systèmes amènent l'opérateur à sauter des étapes dans son raisonnement. Il va plus vite, s'évite une analyse en profondeur, dispose déjà de conseils d'actions, mais sa représentation mentale de la situation change en conséquence. **RASMUSSEN et GOODSTEIN (1985)**, **REASON (1986)** soulignent le potentiel danger de cette évolution qui laisse à l'opérateur l'entière responsabilité de l'exécution d'actes pour lesquels il a tronqué sa démarche intellectuelle d'analyse de la situation.

Ces faits conduisent à s'interroger précisément sur le contenu de la représentation mentale : il s'agit avant tout de connaissances, regroupées fonctionnellement, et transférées de la mémoire à long terme vers la mémoire de travail complétée par des éléments factuels de la situation ; quand il s'agit de schémas, ils sont particularisés aux valeurs de cette situation factuelle.

Le fonctionnement de cette représentation mentale est essentiel au contrôle de processus. **OCHANINE** a développé la théorie de l'opérativité (1981) pour bien souligner le caractère évolutif, déformé, laconique, centré sur le but poursuivi, du contenu de cette représentation.

Cet auteur distingue justement cette représentation opérative, régulatrice de l'action, d'une autre catégorie de représentation dite cognitive qui est un instrument de connaissance centré sur un objet et essayant de le refléter de la façon la plus exhaustive possible.

LEPLAT (1985) préfère au terme de représentation opérative, celui de représentation fonctionnelle. Il lève ainsi une ambiguité possible avec les stades opératoires de Piaget. L'esprit reste cependant le même : la représentation apparait comme la source de la planification, du guide et de la régulation de l'action.

Une étude récente menée à notre laboratoire (**AMALBERTI, VALOT, 1985; AMALBERTI et Al., 1986-1987**) confirme le rôle essentiel de la plasticité de cette représentation en fonction de la perception subjective par l'opérateur des contraintes de la situation et des outils mis à sa disposition.

Nous avons sur une durée de quatre ans mis à plat l'expertise d'un pilote de combat par des méthodes alliant différentes techniques d'entretiens et d'observations en vol réels. Ce travail considérable est poursuivi actuellement par une modélisation informatique des activités mentales du pilote de combat. Cette modélisation est réalisée dans la perspective du développement d'un système de détection et de récupération précoce d'erreurs humaines basé sur un analyseur de contexte temps réel.

Il n'est pas de propos dans cet article de décrire tout le détail des résultats obtenus mais nous en retiendrons trois aspects démonstratifs quant à la plasticité des modèles mentaux et au rôle de la connaissance de l'usager sur son système.

1.1. Nous avons comparé un pilote expert et un jeune pilote opérationnel lors de la préparation d'une mission de pénétration très basse altitude en mauvaises conditions météorologiques (TBAGV). Leur représentation du même ordre de mission est de fait complètement différente : le jeune consacre les 2/3 de son temps de préparation à la phase de navigation TBAGV ; il réalise une approche scolaire de l'objectif et néglige complètement la tactique de etour. Il a interprété l'ordre de mission en fonction de ce qu'on exige de lui habituellement compte tenu de son niveau. Sa représentation de l'action à mener est déformée, laconique pour certains aspects, très riche pour d'autres.

Inversement, le pilote expert consacre peu de temps à la préparation de la pénétration très basse altitude qu'il sait bien maîtriser et étudie plus particulièrement le cadre tactique de l'objectif et du retour. Là encore, la plasticité de la représentation est clairement soulignée. L'exécution de la mission reflète dans les deux cas les particularités de cette préparation et, bien sûr, les résultats en sont sensiblement différents.

1.2. C'est le même type de résultat que l'on observe quand on demande à des pilotes d'expériences différentes de décomposer le plus profondément possible le contenu de leur mission. Les décompositions sont un bon reflet de leur représentation personnelle de la difficulté de réalisation de chaque phase de vol : plus la phase est complexe au sens perception de danger et exigences en technicité, plus elle est détaillée et inversement, plus elle est simple, moins elle est détaillée (figure 1).

Ces deux résultats démontrent que l'opérateur code comme une connaissance particulière l'estimation de ce qu'il croît savoir ; il associe à chaque schéma d'action une méta connaissance décrivant la difficulté concrète de la réalisation pour lui. Cette connaissance est probablement revisée après chaque exécution. Il réserve une place privilégiée dans sa représentation de l'action à la description des séquences qu'il croît avoir du mal à exécuter et résume inversement les séquences qu'il croît connaitre bien.

1.3. Ce type de plasticité est également induite par la connaissance qu'il développe sur les outils mis à sa disposition.

Au niveau de l'exécution sur le système pendant le vol, le contenu des schémas est largement dépendant des connaissances d'univers possédées apr ailleurs sur la fiabilité du système.

Ainsi, en navigation très basse altitude sans visibilité, le pilote dispose du schéma prototypique suivant :

passé la verticale du point tournant,
je vire à la nouvelle route,
je réenclenche le PA,
dès que l'avion est revenu ailes à plat,
je vérifie que j'ai bien programmé sur l'ordinateur le bon but suivant,
je vérifie que j'ai la bonne route, la bonne distance, la bonne vitesse par rapport à mes prévisions de préparation,
j'estime la durée de la branche,
je me détend et j'attend l'arrivée à 5 nautiques du but suivant.

Cette représentation focalisée sur les points d'interactions entre le pilote et son système contient peu ou pas de contrôles sur les automates de pilotage et de navigation. Le pilote sait qu'il dispose d'outils fiables en respectant certaines conditions : être sur le bon mode pour le pilote automatique et pour la centrale à inertie, avoir vérifié récemment (il le fait en début de branche) qu'elle est encore exacte. Il sait que si la centrale est exacte à un point donné, elle sera nécessairement suffisamment exacte à la fin d'une branche de quelques nautiques de long.

Inversement, d'autres exemples de sa connaissance démontrent comment il prend en compte le manque de précision ou de fiabilité des systèmes : il dispose notammment d'un boitier de commande de cap très imprécis par rapport à ses désidérata. Il en déduit de véritables schémas de contournement avec des procédures de pilotage manuel pour s'éviter l'usage de ce système.

De même il doute de la fiabilité du radar dans certains modes (notamment de la stricte horizontalité du plan de découpe). Contrairement au pilote automatique ou à la centrale à inertie, les schémas utilisant ce système sont en conséquence extrêmement détaillés en terme de surveillance du bon fonctionnement. Le pilote pense que pour ces cas précis, son contrôle doit être permanent et qu'il ne peut rien déléguer durablement à ce type d'automate. Ce système de connaissance sur la fiabilité des automates, mis en place par l'expérience, modifie progressivement et profondément sa représentation de l'action à mener.

Chaque partie assumée par le système disparait donc partiellement de la représentation opérative même si les connaissances attenant à ces actions sont possédées par le pilote (elles ne sont dans ce cas plus activées et ne font plus partie intégrante de cette représentaiton fonctionnelle mais peuvent être recueillies lors de la mise à plat de l'expertise).

En cas de faillite du système, le pilote est contraint à reconstruire une représentation adaptee aux nouvelles exigences du contrôle de processus.

En résumé, le contenu de la représentation de l'action développée par le pilote est fonctionnellement déformé par rapport à l'action réelle. Il est centré (égocentriquement!) vers les points réels d'interaction entre système et homme. Tout ce que le système fait seul disparait presque de cette représentation et est remplacé par un "résumé mental".

Ce n'est pas la tâche de l'interface H/M qui est représentée, c'est la tâche de l'Homme gérant l'interface H/M.

Dès lors, chaque automatisme du système devrait logiquement concourir à un appauvrissement de la représentation. Cela est vrai et faux. En fait, il s'agit d'un changement de contenu de la représentation.

Il y a redistribution du partage des tâches. Le pilote gère la tactique de vol et réserve dans sa représentation une place plus grande aux connaissances sur l'Univers de la tâche. Il peut notamment évoquer plus de scénarios possibles et se préparer mentalement à leur résolution. Cette attitude est finalement l'attitude recherchée par les concepteurs de système. Elle est donc à considérer comme satisfaisante. On développe des automatismes en vol pour libérer les mains et les yeux du pilote ... et son esprit. La fiabilité et les performances du système jettent de nouvelles frontières dans le partage des tâches H/M.

Nous venons de voir comment le contenu de la représentation se centrait sur la tâche du pilote et non sur la tâche du système. Ceci suppose l'acquisition préalable d'une connaissance de ce qui est capacité de chacun, et notamment capacité du système lui-même. Le second chapitre envisagé sera donc centré sur l'acquisition des connaissances qui permet justement ce partage de tâches.

II - ACQUISITION DES CONNAISSANCES ET MODIFICATIONS DU PARTAGE DE TACHE

Le parallèle entre acquisition des connaissances et modifications de fonctionnement de l'opérateur est maintenant une notion bien classique. **FITTS et POSNER (1967)** puis **ANDERSON (1985)** distinguent en effet 3 étapes.

L'étape 1 est dite cognitive. Elle correspond à l'acquisition de connaissances déclaratives sur l'action (connaissances *sur la composition des systèmes et leur usage formel dans l'action)*.

A ce stade, ces connaissances déclaratives viennent se greffer à des connaissances générales sur les procédures d'actions, l'exécution proprement dite est nécessairement réalisée pas à pas en faisant appel à toutes les règles possédées.

Une deuxième phase dite "associative" succède à cette première étape. Les premières erreurs dans la compréhension initiale sont progressivement éliminées. Des renforcements sont créés entre connaissances qui "servent" - la connaissance déclarative est transformée en connaissance procédurale.

Il s'agit du premier stade où le sujet peut être considéré comme compétent. Une troisième étape dite autonome, parachève la formation et permet l'acquisition d'automatismes. Les progrès peuvent se poursuivre à l'infini.

Le point essentiel de cette acquisition de l'expertise est finalement l'existence d'un double codage des connaissances : d'un côté des connaissances descriptives théoriques, et de l'autre des connaissances fonctionnelles pratiques. Ce sont ces dernières qui composent les schémas d'actions et donc la représentation mentale de la situation en cours. Le pilote n'a ni le temps ni le souhait de rappeler le détail des connaissances *qu'il possède sur un système donné chaque fois qu'il a à se servir de ce système.* Ainsi, toujours dans le cadre de l'étude sur la mise à plat de l'expertise d'un pilote de combat, il apparaît que l'expert est capable de décrire très précisément l'indicateur d'incidence dont il dispose sur son tableau de bord mais est loin de se servir dans l'action de toutes ses possibilités.

Cet indicateur fournit l'angle du nez de l'avion avec la trajectoire au demi-degré près (échelle chiffrée) ; la valeur est doublée d'une redondance par voyants colorés codant l'angle de trois degrés en trois degrés.

En navigation basse altitude, la seule connaissance fonctionnelle possédée est que "vert, c'est bien". L'expert ajoute qu'il est inutile de lire la valeur précise de cet angle puisque que de toutes façons :

- il n'a pas besoin directement de cette information pour la menée des actions,
- et il n'est pas capable de contrôler la pertinence de cette information ; *il ne sait pas comment elle* est construite dans l'ordinateur !.

Il explique qu'il n'a jamais disposé d'indicateur d'incidence sur les avions précédents. Cette indication n'est pas strictement utile dans la menée de l'action puisqu'il a toujours su faire sans elle.

Il utilise alors l'information disponible en la détournant partiellement de l'intention du constructeur : il ne cherche pas à avoir une valeur précise d'incidence, il vérifie simplement la présence du vert parce qu'il a constaté qu'il est vert chaque fois que la situation est normale et stabilisée.

Ce cas est un exemple d'une *règle plus générale* : l'opérateur utilise préférentiellement les informations de synthèse qu'il peut, par un raisonnement, reconstruire de lui-même et donc vérifier. Il se sait capable d'estimer l'incidence à 3° près, donc utilise cette finesse d'information - plage colorée - ; inversement, il n'utilise pas le demi-degré parce qu'il est incapable d'interpréter et de vérifier la pertinence de cette *information*.

Il considère qu'il peut d'autant plus faire confiance au système qu'il se sait capable de le vérifier. Le paradoxe de cette analyse est que le pilote, une fois son opinion faite, investit l'information d'une certaine fiabilité qu'il ne remet plus en cause par la suite. Il fait confiance. Pour reprendre les termes d'Anderson, la connaissance fonctionnelle est élaborée à partir des connaissances déclaratives avec des justifications précises en termes de facilité d'exploitation et de fiabilité. Mais par la suite, cette connaissance devient autonome et ses justifications initiales ne sont plus évoquées systématiquement.

Un autre exemple concerne l'acquisition de connaissances par les machinistes de salle de contrôle des moteurs sur bateaux de guerre (**BOURGET et al. 1987**). Une alarme remontait périodiquement sur le dispositif indiquant un niveau bas carter d'huile.

Le machiniste disposait par ailleurs des règles de connaissances suivantes "si une alarme apparaît, alors appuyer sur le bouton d'effacement" et
"si l'alarme disparaît, alors conclure que c' est une fausse alarme".

Dans le cas du problème, l'alarme disparaissait deux fois sur trois lors de l'appui sur le bouton effacement. *L'opérateur a alors développé une interprétration cohérente de cette situation* : il n'a pas remis en cause les règles *qu'il connaissait, il n'a pas analysé la panne, il a simplement* déduit que ponctuellement le bouton pouvait se coincer : il était prisonnier d'une représentation mentale extrêmement routinière de la situation. Pourtant, le niveau d'huile était réellement bas, le capteur se découvrait chaque fois que le bateau prenait du gîte, déclenchant ainsi l'alarme qui s'éteignait spontanément quand le bateau revenait à l'horizontale. L'effacement dû à l'appui du bouton était simplement une coïncidence.

Dans ce cas, l'opérateur est prisonnier d'une certaine simplicité de la représentation mentale qu'il utilise, largement basée sur des processus automatiques. Il est tout à fait capable de faire l'analyse à postériori mais ne l'est pas sur le moment ; il cherche à résoudre son problème dans le cadre de sa représentation sans faire l'effort de la réviser.

Il s'agit bien là d'un autre point fonctionnel essentiel de la représentation : elle guide l'opérateur

mais elle l'enferme également dans une "vision limitée du monde" suffisante et pertinente dans la très grande majorité des cas (et particulièrement économique en termes de ressources mentales, d'où son avantage) mais ponctuellement dangereuse. Il est extrêmement difficle pour l'opérateur de rompre cette représentation pour en rechercher une mieux adaptée.

Or, et c'est là un trait fondamental, les systèmes automatiques favorisent considérablement l'*existence* de représentations simplifiées.

C'est ce cas que l'on observe typiquement avec les directeurs de vols en Aéronautique civile (**AMALBERTI à paraitre**).

Les pilotes apprennent rapidement voire à leurs dépens, que les indications données par ce directeur *de vol sont plus pertinentes que toutes variations personnelles (car* elle intègrent à la fois la pente, la vitesse, etc...). Cette information de direction de vol est construite en permanence par le calculateur de bord. On constate, en suivant la progression des équipages trois phases bien individualisées :

- une première, *formelle*, où les élèves apprennent un certain nombre de règles de base sur les profils de vol à respecter (pente max ... min; vitesse max ... min....) ainsi qu'une connaissance appronfondie sur les modes P.A. et les directeurs de vols embarqués. Il s'agit en quelque sorte de connaissances déclaratives.

- une seconde, où ils découvrent réellement le directeur de vol en simulateur. Ils en sont souvent surpris car son suivi manuel demande de la concentration. Presque systèmatiquement les cas où le directeur de vol est mal suivi se soldent par des dégradations du vol, objets de commentaires et de debriefings de la part du moniteur et constatés *d'ailleurs par* l'élève *lui-même.* C'est le temps de l'exécution de la tache pas à pas. Les renforcements positifs successifs (suivi de directeur de vol) et négatifs (dégradation par non suivi) amènent progressivement l'élève à bien suivre ce directeur. Une partie des connaissances de bases a été procéduralisée. Cette partie est pratique et s'appuie sur une axiomatique de fiabilité du directeur de vol. Il n'y a jamais eu *acquisition* de connaissances fines sur la logique utilisée dans le directeur de vol à telle ou telle phase de vol. Il y a transfert de "fiabilité" par une règle du type "si le constructeur a dit que c'est bon et que j'ai vérifié sur quelques cas exemples que c'est bon, alors c'est nécessairement et toujours bon".

Or, un certain nombre de contextes font que le calculateur peut être amené pendant plusieurs secondes, et notamment dans des phases de vol très délicates à fournir des informations erronées. Il peut en être ainsi dans le cas où le pilote ordonne par directeur interposé des vitesses ou des altitudes trop tôt, trop tard... auquel cas le directeur de vol applique l'ordre et crée un écart potentiel avec la trajectoire que voudrait suivre le pilote.

Le pilote ne modifie pas la règle de base dont il dispose sur la fiabilité du système ; il juxtapose simplement une nouvelle règle de portée limitée : "si au décollage ou à la remise des gaz, le directeur de vol indique un pitch inférieur à 5-6°, alors afficher 10° et attendre un moment pour resuivre le directeur". *La fiabilité du système n'est pas remise en cause et ce qu'il en* reste dans la représentation mentale de l'action est toujours aussi dénué d'analyses et de contrôles complémentaires. Le pilote se place lui-même en situation d'exécutant.

III - CONCLUSION - DISCUSSION

Lors d'un travail, l'homme anticipe et se représente mentalement le travail qu'il va avoir à faire. Le contenu de cette représentation va servir de guide et de régulateur lors de l'exécution. Ce qui n'est pas dans la représentation ne sera pas dans l'action sauf si il y a reélaboration d'une *nouvelle représentation* des faits, ce qui est toujours couteux en termes de temps et d'énergie.

La représentation du travail que l'homme s'assigne dans la relation homme-machine est fortement conditionnée par la capacité et la fiabilité qu'il affecte au système. A partir d'un certain seuil de fiabilité conféré au système, le partenaire humain se désengage de la tache faite par le système. La représentation de son travail s'appauvrit quant à cette tache devenue automatisée. Cet appauvrissement peut s'accompagner d'un enrichissement dans d'autres domaines notamment : la tactique, la reflexion sur la mission ... etc.

Il s'agit bien du but poursuivi en aviation militaire.

Cette position de superviseur face à des systèmes hautement fiables n'est probablement et malheureusement que formelle.

Déconnecté du contrôle de processus, possédant peu de connaissances sur le système lui-même qui soient utilisables efficacement *(il faudrait des connaissances procédurales* et non déclaratives) et ce, essentiellement, parce que la pratique est rarissime, le pilote développe avec beaucoup de difficultés une représentation mentale de sa tache correspondant effectivement à une tache de supervision. Il délégue beaucoup au système et ne garde dans sa représentation de l'action que quelques "noeuds" de passage qui correspondent étrangement aux seules étapes communes entre ce qui *était avant "sa tache" et ce qui est maintenant* "la tache des systèmes". Il ne supervise plus le controle de processus au sens vrai du terme mais simplement le passage à des noeuds, accessibles à sa compréhension, qui lui témoigne que le système marche bien, et qui peuvent être distants de plusieurs minutes.

La tache de superviseur est effectivement effectuée pour les noeuds mais ne l'est plus du tout pour les séquences intermédiaires avec tous les risques que cela comporte.

Une fois acquise, cette croyance dans la fiabilité agit comme un filtre dans les règles de connaissances qui vont être procéduralisées pour être utilisées effectivement comme procédures d'actions et contenus des représentations.

En conclusion, les systèmes hautement fiables peuvent être catégorisés en deux :

- ceux dont l'opérateur perçoit la haute fiabilité et dont le fonctionnement est autonome : cas des centrales à inerties, cas du pilote automatique ... etc.
  Dans ce cas la représentation de l'action développée par l'opérateur ne contient plus qu'un résumé superficiel de la séquence automatisée et l'opérateur décentre sa représentation sur le début et la fin des séquences automatisées, là où il a à intervenir. Il n'exerce pas de contrôle particulier sur la séquence automatique car il n'y a plus dans la représentation mentale de l'action de règles spécifiques pour le contrôle de ces actions automatisées (ce qui ne veut pas dire que ces règles n'existent pas ... elles sont même parfois possédées).

  Il s'agit de fait d'un partage vrai des tâches entre homme et système qui existe même si les consignes recommandent d'autres voies.

  L'opérateur "sort complétement de la boucle" au *niveau de ces* automatismes. Toute situation incidentelle est alors grave à de multiples égards :

  . détection difficile par manque de controle,
  . diagnostic difficile par manque ou par pauvreté de la représentation de la situation incidentelle.

  En quelque sorte, plus le matériel est fiable, moins l'opérateur est lui-même fiable face à des anomalies de ce matériel.

- ceux dont l'opérateur perçoit la haute fiabilité et *dont* le fonctionnement suppose un opérateur en position d'exécutant d'ordres : directeur de vol, ...

  Dans ce cas, la *représentation de* l'action ne contient pas non plus de structure de contrôle du système. Elle se limite à l'exécution manuelle et sans écart des actions commandées.

  Le paradoxe est alors que l'homme croit qu'il est d'autant plus fiable qu'il suit le système, parce qu'il le sait encore plus fiable que lui.

  L'erreur survient souvent dans ce cas en manipulant des commandes du système qui sont interactives avec le processus mais dont la représentation mentale *dissocie les relations*, fautes de connaissances suffisantes.

WIENER et CURRY (1980) s'interrogent sur les raisons qui poussent finalement les constructeurs à automatiser de plus en plus puisque l'on sait les effets négatifs que cela comporte sur la fiabilité de l'homme. Ils évoquent plusieurs raisons : technologie disponible, sécurité, *économie*, fiabilité, simplicité de la maintenance, réduction de la charge de travail, précision des manoeuvres de vol, *flexibilité des afficheurs*.. ...etc.

Ils proposent également une solution, celle du "flight management by exeption" qui consiste en tout lieux et en dépit de toutes règles à autoriser le pilote à faire ce *qu'il veut avec son avion* ; les systèmes ne signalant que les sorties du domaine de sécurité. Il s'agit ici de renverser complétement la tendance actuelle et, tout en gardant la technologie, de rendre complètement manuelle la conduite du vol. C'est une proposition défendable, mais qui a bien sûr ses limites.

Nous y mettrons côte à côte une autre idée : les interfaces *H/M* ont été *construits* pour permettre à l'opérateur de diriger les machines. Pendant longtemps, on a adapté les informations et les commandes pour qu'elles deviennent utilisables par l'homme. Cela s'appelait l'ergonomie mais le mot n'existait pas.

Aujourd'hui on veut trouver une place à l'opérateur qui est présent face à des systèmes automatiques hautement fiables. On lui affecte le rôle de superviseur,... mais on ajoute qu'il *serait regrettable* qu'il intervienne sur le système sans raison justifiée. Le champs d'action résultant est étroit. **BRAINBRIDGE** (cité in **BISSERET, 1984**) *montre portant* que plus un système de contrôle est automatisé plus la contribution de l'opérateur humain y est cruciale. En effet, ce qui reste au superviseur, c'est justement ce que le concepteur *n'a* pas su automatiser parce qu'il n'a pas su le prévoir. **BISSERET** dans le même article, s'opposant à **WIENER et CURRY**, pense que la solution n'est pas de diminuer les automatismes car l'activité restituée ainsi *à l'opérateur* serait interactive, "réglée", et de toutes façons n'aiderait pas à la résolution d'incidents. Il conseille de donner aux opérateurs des tâches "qualifiantes" durant les périodes de temps libre pour les préparer à faire face aux situations anormales. Là encore ce point de vue est défendable mais connait ses limites.

Ainsi, au bilan, maintenant que l'ergonomie classique s'est développée, force est de constater que le champs des demandes impose une nouvelle évolution radicale de cette discipline pour répondre à des questions d'une extrême compléxité portant sur le fonctionnement mental de l'opérateur.

Ces réponses ne peuvent plus être du seul domaine de l'ergonome car elles touchent à *la philosophie* de la place de l'homme dans le travail.

Pourtant, il y a plus que jamais à faire et à dire .... à moins que les ingénieurs ne souhaitent concevoir des *robots* ...

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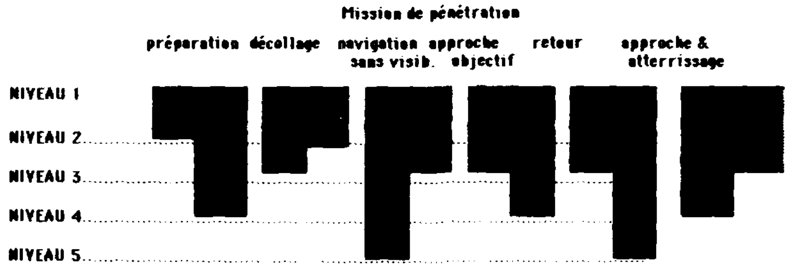
FIGURE 1

Résultats synthétiques de la décomposition de la tâche effectuée par tous les pilotes en début d'analyse.

En noir : profondeur moyenne de la décomposition des pilotes sebutants dans l'exécution effective de la mission,

En grisé, profondeur moyenne de la décomposition pour des pilotes experts

Les jeunes pilotes privilegient la phase de navigation sans visibilite et negligent relativement la tactique sur l'objectif et au retour



Les cinq niveaux de décomposition sont préfixés par une première analyse de tout le matériel obtenu auprès des pilotes. Ils correspondent à la décomposition maximale, tout sujets confondus, dont on dispose. Chaque travail individuel est par la suite réexaminé avec ce codage en niveaux identique pour tous

Le schéma ci-dessous donne un exemple de décomposition.

Préparation

N1

N2 **lire paramètres**..... **préparer la route**..... **préparer** ... **horaire**....**etc**
ordre de mission

N3 **lire lieu objectif** ... **lire heures imposées** . **demander météo** ...**etc**

N4 sortir carte 250 000°... **tracer zone objectif**...

N5 sortir abaques mesures (patate)....

INTERFACE HOMME/MACHINE EXPERTE
POUR UNE CABINE D'AVION DE COMBAT

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ABSTRACT :

Through developping navigation and attack systems on combat aircraft and by analysing the new operational concepts, an always increasing workload is required from the pilot.

AMD-BA have been concerned with this problem for many years in designing each different combat aircraft.

An important part of the workload lies in getting the management informations by the pilot. In case of very low level flying, getting these informations become especially tight : the pilot cannot divert his attention from outside the cockpit to watch over the vehicule and its system.

For this reason, modern fighter's cockpit - such as on the different versions of the MIRAGE 2000 and now on the RAFALE - are already oriented on using head-up terminals for displaying built-up informations. Enhancements have been made on displays in order to increase the capacity of collimated data.

In addition, synthetic voice warnings are already used and days after days, the place of speech processing is increasing.

For the future, AMD-BA are studying the benefit of artificial intelligence technics for improvement of displays and spoken messages in working at two levels :

- in the pertinence of information depending on the phases of the mission and especially on the pilot workload which is inferred by the expert system,
- in the suitable synthetic information to help the pilot in decision making.

AMD-BA are working on an Expert System which purpose will be precisely to operate at these two levels depending both on its importance with respect to the mission and on the workload inferred by the Expert System in the different steps of the mission.

1. INTRODUCTION

Le but de cette présentation est de montrer tout d'abord quels sont les soins apportés depuis longtemps à l'organisation des postes d'équipage des chasseurs aux AMD-BA, quelles sont les tendances qui se dégagent et surtout, de quelle façon les techniques d'intelligence artificielle peuvent intervenir pour faire progresser la conception de nos cabines.

2. ORGANISATION DES POSTES D'EQUIPAGE

Nous considèrerons quatre thèmes principaux, déterminants dans la conception de la cabine d'un chasseur :

- l'installation du pilote,
- le pilotage tête haute associé au fonctionnement des commandes de vol,
- l'aide au pilote pour la conduite de la machine,
- les nouvelles technologies des équipements de dialogue.

a. L'INSTALLATION DU PILOTE

Dans l'étude de la cabine, comme dans celle de tout poste de travail, un grand soin doit être apporté à l'environnement du pilote. La tendance, pour les chasseurs modernes, est de faire appel à des sièges éjectables, "inclinés" par opposition aux sièges éjectables installés jusqu'ici tant sur les avions des AMD-BA (MIRAGE III, MIRAGE IV, MIRAGE 5, MIRAGE F1, MIRAGE 2000, SUPER-MIRAGE 4000, ALPHA JET) que sur les avions étrangers, en particulier les F5, F14, F15, F 18 ou TORNADO. L'installation d'un siège conférant un angle de dos supérieur à 30° d'inclinaison par rapport à la référence verticale du fuselage sur le RAFALE A actuellement en essais en vol, nous a permis de conforter les résultats que nous avions obtenus au cours d'études préliminaires menées avec le soutien des Services Officiels français, et en liaison avec le LAMAS et le CERMA. Cette installation permet d'exécuter des manoeuvres soutenues à fort facteur de charge dont est capable la machine en diminuant notablement la charge imposée au pilote, ce qui lui permet une meilleure efficacité. Ce gain se retrouve aussi dans les accélérations transitoires.

Ces bons résultats sont les fruits d'un travail important mené aux AMD-BA où l'utilisation d'un siège incliné n'a pas été considérée isolément mais a fait l'objet d'une étude complète et approfondie de tous les éléments relatifs à l'installation du pilote :

- . accoudoirs
- . manche et manette et
- . commandes temps réel associées
- . terminaux de visualisation
- . visibilité extérieure

b. *PILOTAGE TETE HAUTE ET COMMANDES DE VOL*

Les AMD-BA accordent une très grande importance aux étroites relations que les commandes de vol doivent avoir avec tous les éléments de l'avion et le pilote. Les technologies nouvelles des commandes de vol, en particulier l'utilisation de calculateurs numériques et de liaisons électriques et bientôt optiques, permettent des sophistications qui décuplent leur puissance et qui rendent cette étroitesse de liens encore plus fondamentale.

C'est en particulier le cas avec les informations de pilotage à présenter au pilote. Depuis longtemps, les AMD-BA ont démontré l'intérêt du pilotage tête haute, dans toutes les configurations de vol et, en particulier, en cas de vol à basse altitude.

Il est sans doute inutile de s'appesantir ici sur le fait que le pilotage tête haute constitue une nouvelle méthode de pilotage dont l'intérêt est de présenter directement d'une part la trajectoire de l'avion, avec le vecteur-vitesse (par référence à l'horizon), et, d'autre part, l'évolution de la vitesse sur trajectoire, avec le repère d'énergie potentielle. Un exemple de figuration tête haute complète est donnée (figure 1) où se trouve notamment, en plus des symboles cités ci-dessus, un réticule de guidage ILS, utilisable comme un directeur d'ordre pour le contrôle de la trajectoire.

La coopération entre cette présentation et les commandes de vol est intégrale et trouve sa puissance dans le fait que le pilote peut agir de façon découplée, à court terme, sur le vecteur-vitesse par action sur le manche (devenu manche latéral), et sur l'énergie par action sur la manette. Cette façon de contrôler l'avion permet de meilleurs temps de réponse que le pilotage d'un paramètre intermédiaire (assiettes e.g.) et son principe est tellement séduisant que, les AMD-BA ont proposé puis expérimenté en vol avec le RAFALE A, une extension de cette méthode en donnant à la manette non plus le rôle de commande des moteurs mais la fonction globale de commande du bilan traînée-poussée. Il faut d'ailleurs remarquer que, contrairement aux usages, cette manette est unique alors que l'avion est bimoteur !

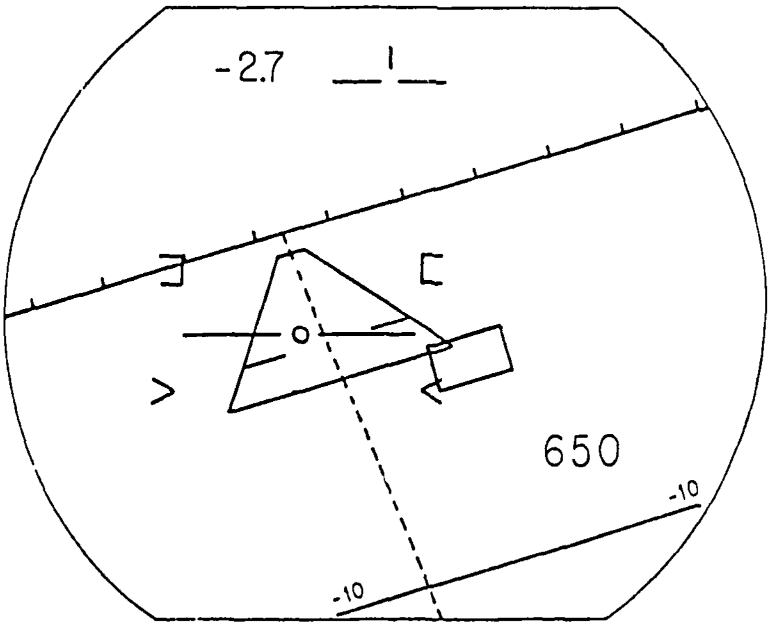

FIGURE 1 : Présentation d'informations de pilotage tête haute

Comme les commandes de vol intègrent les limitations de domaine, on aboutit à un pilotage sans soucis, tout en augmentant la précision, l'efficacité et le niveau de sûreté du pilotage. La superposition des réticules sur le monde extérieur supprime le besoin d'accommodation entre extérieur et planche de bord et améliore la perception des différents dangers : reliefs du terrain, superstructures telles que antennes, pylônes ou lignes à haute tension, autres aéronefs...

Enfin, le pilotage tête haute permet une bien meilleure transition entre les différents modes de pilotage automatique ou assisté et le pilotage "manuel", le pilote restant beaucoup mieux "dans la boucle", ce qui est fondamental pour sa rapidité de réaction en situation anormale.

Dans l'étude des avions futurs, les principales tendances recherchées par les AMD-BA sont :

- l'utilisation de collimateurs tête haute holographiques qui apportent à la fois un agrandissement du champ (tant instantané que total) et de meilleures caractéristiques photométriques permettant d'obtenir à la fois de très bons contrastes de symbologie, même soleil de face, et une très bonne perception du paysage, en particulier en cas de luminosité faible. C'est d'ailleurs avec beaucoup de satisfaction qu'un collimateur de ce type, réalisé par THOMSON-CSF, est utilisé, depuis le premier vol, sur le RAFALE A ;

- l'augmentation de la fiabilité de la présentation des informations en tête haute, pour rendre ce mode de pilotage encore plus sûr et chercher à éviter les comparaisons entre informations tête haute et tête basse, encore de mise dans de nombreux chasseurs ;

- la mise en oeuvre, par des réticules simples, fonctionnant toujours en trajectoire/énergie, de guidages de très haut niveau,

  - intégrant les nombreuses données qu'est susceptible de connaître la machine,

  - optimisant différents critères, en fonction du type de mission et de la phase en cours : dépense de pétrole, respect d'un horaire, évitement d'obstacles ou de menaces...

  Dans ce domaine, on verra plus loin que l'intelligence artificielle peut avoir des retombées intéressantes.

c. ASSISTANCE AU PILOTE

En tant que concepteurs du système complexe et très intégré que constitue un chasseur moderne, les AMD-BA ont la volonté de fournir au pilote une machine dans laquelle celui-ci se sente en confiance.

La régulation de différents équipements complexes (moteurs, e.g.), le fonctionnement des circuits et des servitudes, l'exécution automatique de certaines tâches sont conçus avant tout pour libérer le pilote. En fait, il est classique de constater que la juxtaposition de ces "automatismes" aille à l'encontre du but initial. Certains ne manquent pas de parler alors d'automatismes mal conçus, en particulier lorsqu'ils nécessitent une surveillance de la part du pilote, d'autant plus difficile à mener que les moyens de contrôle sont alors, dans bien des cas, réduits et la conception des alertes ou alarmes, peu adaptée.

Dans la démarche menée aux AMD-BA, la mise en place de toutes ces assistances entraîne une refonte complète de la conduite de la machine dans le but (idéal) de réaliser une cabine libre de toute surveillance. L'intégration des systèmes est à la base de cette refonte qui permet aussi de simplifier les procédures, de réduire les signalisations et les postes de commande spécifiques. Un exemple, ponctuel mais révélateur : Sur le RAFALE, le relâchement du frein de parc fait passer les centrales à inertie dans le mode Navigation.

Un domaine capital à ce titre est la philosophie de détermination et de présentation des alarmes. L'intégration des systèmes permet de gros progrès dans ce domaine, d'autant plus appelé à évoluer, que les traitements informatiques se répandent à tous les éléments de l'avion et que le traitement de l'information devient possible à différents stades. La réduction significative des moyens conventionnels d'alarmes (voyants lumineux) opérée sur le RAFALE A est un indice reflétant cette évolution. L'annonce des alarmes fait appel à une voix synthétique, capable d'annoncer plus de trente séquences sonores et vocales différentes, bien discernables par le pilote. En parallèle à une signalisation visuelle dans les terminaux de visualisation, elle constitue un moyen très efficace de présentation au pilote de toute situation anormale, à condition qu'elle soit détectée par la machine.

Les progrès à faire sont bien sûr dans la détermination de ces états anormaux qui doit être à la fois la plus pertinente possible, très sûre et très fiable. Voilà bien sûr un domaine clef où l'utilisation des systèmes experts peut se révéler prometteuse afin d'aboutir à une signalisation :

- au moment opportun,

- au bon endroit,

- conseillant la bonne action.

d. NOUVELLES TECHNOLOGIES DES EQUIPEMENTS DE DIALOGUE

Les AMD-BA sont très attentifs aux possibilités offertes par les nouvelles technologies dans tous les domaines participant à la conception des avions. L'intérêt technique du RAFALE A a été d'ailleurs de démontrer la validité de plusieurs d'entre elles que ce soit pour les structures (composites, aluminium-lithium...)pour les commandes de vol, ou pour la cabine.

Le cas du collimateur tête haute en est bien sûr un très bon exemple. Mais cette cabine a permis aussi de juger d'autres réalisations.

Un terminal de visualisation d'un type tout à fait inhabituel est aussi utilisé depuis le premier vol du RAFALE A. Il s'agit d'un Collimateur Tête Moyenne (CTM), situé en-dessous du collimateur tête haute, en continuité de champ avec lui. Il procure une image collimatée dans un champ bien plus important que le champ qu'aurait un terminal classique de surface équivalente situé en cet endroit. Cette image peut être purement synthétique pour la présentation classique d'informations, mais on peut aussi utiliser ce terminal pour présenter la vidéo issue d'un capteur, et même, de façon plus originale, présenter l'image générée par un capteur électro-optique angulairement conforme à ce que le pilote verrait si la planche de bord était transparente.

D'autres technologies prometteuses sont aussi en cours d'évaluation : cristaux liquides, synthèse vocale, commande vocale...

Au-delà de ces expérimentations, les AMD-BA recherchent par la mise en oeuvre de ces techniques, l'obtention d'un dialogue plus étroit et donc plus efficace entre le pilote et la machine, et ces études de niveau technologique sont accompagnées d'une réflexion sur leur utilisation et sur les principes de représentation de l'information les plus adaptées. Un axe de recherche très riche est la représentation d'informations connues dans des bases de données, relatives au terrain en particulier, cette représentation pouvant s'imaginer en deux dimensions, trois dimensions et même en relief.

C'est dans ce contexte que les techniques de l'Intelligence Artificielle ont bien sûr parues dignes d'intérêt et c'est ce que nous en attendons qui est développé dans la suite de cet exposé.

3. APPORT DES TECHNIQUES DE L'INTELLIGENCE ARTIFICIELLE

Dans le futur, le calcul symbolique, utilisant les techniques de l'Intelligence Artificielle peut apporter des solutions efficaces et intéressantes pour les interfaces homme-machine des prochaines générations d'avion.

En particulier, des "systèmes à bases de connaissances" embarqués permettront de rendre ces interfaces très adaptées au pilote, à sa charge de travail et à sa mission.

a. Approche nécessaire

Pour utiliser avec profit des "systèmes à bases de connaissances" à bord, il faut avoir résolu un certain nombre de problèmes de natures diverses :

- Assembler et formaliser l'expertise correspondante. Celle-ci porte sur :
  - + des aspects techniques comme :
    - le savoir-faire tactique (évasives, procédures d'urgence, mise en oeuvre des armes) ;
    - le savoir-faire système (l'avion et ses ressources, l'énergie, l'armement, l'avionique,...);
    - le savoir-faire opérationnel relatif à l'environnement (relief du terrain, défenses adverses,...);
    - le savoir-faire stratégique relatif à la mission (évaluation des risques et efficacité) ;
  - + et sur des aspects plus "psychologiques" dépendant d'avantage de la nature humaine et de son comportement dans un milieu stressant (évaluation des capacités de raisonnement du pilote en fonction de l'environnement et des situations).

- Définir des traitements symboliques embarquables capables de performances temps réel.

Dans un tel environnement les temps de réaction nécessaires à l'échelle du pilote sont de l'ordre d'une fraction de seconde à quelques secondes.

- Avoir la possibilité d'utiliser toutes les informations disponibles à bord : tant au plus bas niveau comme les résultats bruts des mesures des capteurs qu'à un niveau plus élaboré à la sortie d'algorithmes spécialisés dans le traitement du signal. Cette deuxième catégorie d'information sera d'ailleurs prépondérante dans la "base de faits" des "systèmes à bases de connaissances".

b. Méthode envisagée

Le but est de fournir une aide "intelligente" au pilote au moyen d'une interface experte ou **module de communication expert.**

Cette interface doit donc réaliser les fonctions suivantes :

- Filtrer de façon pertinente les informations disponibles à bord ;
- Fournir une aide à la décision :
  - + en présentant les suggestions d'action et les vérifica d'hypothèses,
  - + en effectuant des prédictions sur l'évolution de la situation et sur la charge de travail du pilote,
  - + en rendant compte de la surveillance de l'avion et de ses systèmes : c'est-à-dire témoigner de la bonne prise en charge des tâches qui relèvent d'automatismes ou dont le temps de réponse demandé est très court alors qu'elles exigent l'examen d'un grand nombre de paramètres.

L'interface experte doit donc se situer dans la boucle Pilote-Système.

La réalisation de cette interface passe par :

- L'étude de la démarche du pilote (actions et raisonnements) dans la mission de pénétration basse altitude,
- La réalisation d'un modèle général qualitatif de celle-ci qui peut se symboliser de la façon suivante :

1) Suivi de la bonne exécution de la mission (mode normal) puis en cas d'écart :

2) Détection de l'évènement "anormal" (évènement perturbateur dans le déroulement préparé de la mission).

3) Evaluation de la situation en fonction de cet évènement et des autres paramètres caractérisant cette situation.

4) Prise de décision du pilote en fonction de cette situation qui se traduit par une ou plusieurs actions successives à entreprendre.

5) Exécution des actions désirées.

Pour réaliser ce type de décision-action, certains travaux (1) ont permis d'identifier trois types de comportements humains qui sont cohérents avec le modèle ci-dessus.

- Le comportement réflexe où, à une situation reconnue donnée, correspond une action immédiate pour laquelle il n'y a pas d'optimisation.
- Le comportement tactique où, à une situation reconnue donnée, un raisonnement basé sur des règles issues de l'expérience, permet de décider de l'action à faire (raisonnement à court terme).
- Enfin le comportement stratégique basé sur la reconnaissance d'une situation nouvelle, mais où le raisonnement basé sur des expériences variées permet de déterminer le comportement qui correspondra "au mieux" à la situation découverte et qui pourra éventuellement être remis en cause ultérieurement (raisonnement à long terme).

Ces deux derniers comportements résultent également des capacités de prédiction du pilote sur l'évolution de la situation en fonction des données présentes.

De plus, des travaux réalisés en France au CERMA ont eu pour but de "modéliser" le comportement spécifique des pilotes dans ce type de missions et ont permis de réaliser des "schémas types" définissant la structure de leur raisonnement, leur façon de gérer le temps et de gérer leurs propres limitations.

Ces travaux pourront être le point de départ de l'élaboration de la base de connaissances spécifique du **module de communication expert**. Cette base servira au module pour évaluer la charge de travail du pilote dans les différentes phases de la mission.

4. EXAMEN DES PROBLEMES SPECIFIQUES DE LA COMMUNICATION PILOTE-INTERFACE EXPERTE

a. Communication pilote-module (figure 2)

Comme dans le cas d'un opérateur durant un processus complexe (2), la communication avec le pilote doit s'établir en tenant compte des contraintes suivantes :

- Donner au pilote les moyens de reconnaître l'état de fonctionnement de ses systèmes embarqués et les caractéristiques du contexte extérieur (situation tactique, menace, météo, etc...),
- Donner au pilote les moyens d'évaluer la situation résultante,
- De prendre en compte les exigences particulières des pilotes dans ce type de mission

Cela impose d'avoir, dans ce "module de communication expert" :

- Une certaine représentation de l'avion et de ses systèmes.
- Des moyens de visualisations très souples et riches, adaptés au problème (mission).
- Des moyens de communications pilote-machine complémentaires comme la commande, la synthèse et le dialogue vocal pour l'introduction d'observations du pilote.
- Une base de connaissances spécifique adaptée au problème de la communication pilote machine.
- Un accès à la base de faits commune aux autres systèmes experts du copilote électronique, ce qui pose, bien sûr, le problème de l'utilisation d'une architecture "multi-experts".

b. Fonctionnalités du **module de communication expert**

Ce module doit permettre les fonctionnalités suivantes :

- Utiliser les informations (synthétisées) sur le contexte opérationnel et sur l'état des systèmes embarqués disponibles dans la base de faits du copilote électronique.
- Evaluer en fonction des phases de la mission (donc de la charge de travail connue, évaluée et prévue, du pilote) et de l'importance des événements, la meilleure présentation des informations au pilote (sous forme de visualisation ou de message vocal).
- Avoir la possibilité d'être interrogé par le pilote (sous forme de dialogue vocal par exemple) sur un raisonnement ou sur des prédictions en fonction de certaines hypothèses (What if ? ...).
- Avoir une base de connaissances indépendante des autres systèmes experts embarqués mais être capable de partager les informations de tous niveaux.

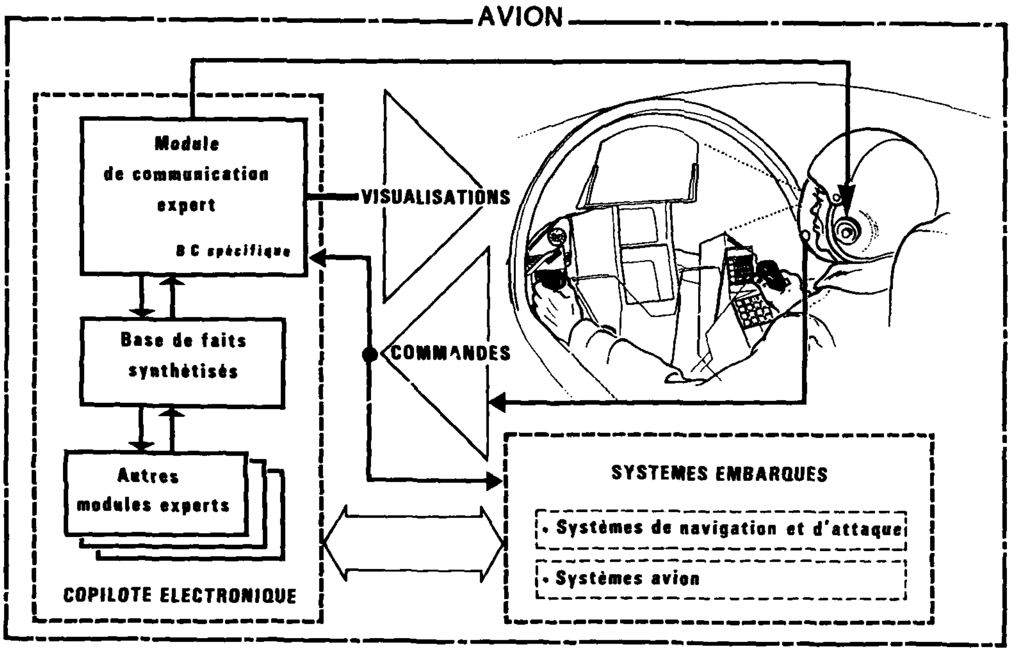

FIGURE 2 : Intégration du module de communication expert

5. ACTIVITES D'AMD-BA DANS LE DOMAINE DES INTERFACES POUR L'ASSISTANCE AU PILOTE

a. Dans le domaine de la présentation des informations de pilotage

Nous avons vu les travaux réalisés par notre société ; la symbologie a déjà fait l'objet de longues études et a abouti aujourd'hui à une qualité reconnue des pilotes.

Par rapport aux méthodes de calcul classiques, le calcul symbolique pourra permettre la prise en compte d'un plus grand nombre de données et plus de souplesse de traitement pour l'animation de cette symbologie.

Nous avons en particulier prévu d'étudier un "système à base de connaissances" spécialisé dans la gestion et la présentation de l'énergie de l'avion pour le pilotage.

b. Dans le domaine des mécanismes de raisonnement

Nous avons entrepris avec le soutien des Services Officiels Français :

- une étude avec le Laboratoire d'Informatique Fondamentale et d'Intelligence Artificielle (LIFIA) sur le raisonnement temporel et incertain ;
- une étude avec l'Electronique Serge Dassault sur le thème de l'aide à la compréhension des pannes et la gestion des procédures d'urgence à bord des avions de combat.

Dans cette étude nous abordons deux points essentiels :

+ L'aspect système expert temps réel embarquable où seront étudiés la compatibilité de l'approche Intelligence Artificielle avec les contraintes imposées par le temps réel, les capacités mémoires et les traitements à mettre en oeuvre pour respecter les temps de réponse imposés par l'embarquabilité d'un système d'avionique.

+ L'aspect génération d'informations pertinentes correspondant à une analyse de la situation de l'avion et à un choix, en fonction des résultats de cette évaluation, des informations à présenter au pilote en fonction des phases de la mission. Par exemple, la détection d'une anomalie dans le freinage ne doit pas être traitée et présentée au pilote de la même façon lorsque l'avion est à Mach 1,6 30.000 ft ou lorsqu'il est en approche avant atterrissage.

c. Dans le domaine de l'aide à la décision embarquée

Nous avons entrepris, également avec le soutien des Services Officiels Français, une étude de faisabilité d'aide à la décision par un copilote électronique dans une mission d'avion de combat. Dans ce cadre précis, et aussi de manière plus générale, nous étudions l'adéquation de l'ergonomie de présentation à la charge de travail du pilote dans les différentes phases de sa mission. Nous cherchons en particulier à établir les possibilités d'un dialogue entre le pilote et sa machine par l'étude de :

- La complémentarité des messages visuels et sonores
- L'apport de la présentation stéréoscopique des aides au pilotage et de la symbologie
- La possibilité pour le pilote d'introduire dans son système (au moyen de la commande vocale) des informations relatives à des observations faites au cours du vol.

Il s'agit dans ce dernier cas, d'étendre les capacités de la commande vocale actuelle à la compréhension d'un vocabulaire assez défini et structuré adapté aux observations potentielles du pilote.

On imagine facilement l'intérêt d'une telle possibilité pour enrichir la base de faits du "système embarqué" et de mettre à jour l'élaboration de la situation.

d. Dans le domaine des techniques de l'Intelligence Artificielle

AMD-BA fait un effort important en Recherches et Développement (en particulier : langage naturel, diagnostic de panne, représentation structurelle et fonctionnelle de systèmes, aide aux spécifications, CAO, architecture "multi-experts" ...) qui auront des retombées dans l'aide au pilote et dans sa communication avec la machine.

6. CONCLUSION

Il ressort de cette analyse que les cockpits des avions d'armes ne cessent d'évoluer au fil des possibilités offertes par les nouvelles technologies. Ces technologies font évoluer les principes de conception et de fonctionnement des interfaces entre le pilote et sa machine.

L'Intelligence Artificielle s'inscrit dans ce mouvement et va s'installer à bord des avions d'armes. Son apport pourra se révéler capital, car il va contribuer à déplacer le niveau des rapports que le pilote entretient avec son avion et constituer un véritable copilote électronique. Celui-ci, déjà capable de fournir au pilote des informations sur les différents constituants des systèmes embarqués, sur le véhicule, sur le monde extérieur et ses composantes favorables ou hostiles, va bientôt pouvoir raisonner en utilisant ces informations et assister le pilote en lui fournissant en outre des prévisions d'évolution, des conseils sur l'attitude à adopter...

Ce niveau supérieur de rapport entre l'homme et sa machine va contribuer à l'efficacité opérationnelle de l'ensemble. C'est l'une des voies qui permettront de faire face aux situations complexes et menaçantes que les forces aériennes auront à affronter dans les années à venir. Il sera envisageable d'étendre le domaine d'emploi des avions et de leurs systèmes à des conditions difficiles telles que le vol à très basse altitude et à grande vitesse, l'attaque de nuit et/ou par mauvais temps, le combat multi-cibles, etc...

Le rôle du pilote évoluera mais ses facultés seront encore mieux mises à profit pour la conduite générale de la mission, et surtout, pour la prise de décision face à des situations imprévues. Ce qui rendra sa place dans la machine toujours aussi importante.

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ENSEIGNEMENTS TIRES DE L'UTILISATION DE NOUVEAUX SYSTEMES DE COMMANDE.

par

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RESUME.

L'extension de l'informatisation à bord des avions de combat permet d'introduire de nouvelles formes d'interfaces pilote-machine.

L'architecture de la cabine du démonstrateur RAFALE est conçue à partir de ces techniques. Ainsi l'angle d'inclinaison supérieur à 30° du siège pilote, destiné à améliorer la résistance aux facteurs de charge élevés, entraîne des conséquences importantes. Parmi ces conséquences on peut citer la position très couchée du pilote, le pilotage par manche latéral, la centralisation des commandes sur clavier multiplexé, la perte de l'accès physique à la majeure partie du tableau de bord qui implique la nécessité de désigner des étiquettes sur les écrans à partir d'un "joy-stick".

Avant d'être complètement implantée sur RAFALE, la commande vocale a fait l'objet d'essais en vol sur MIRAGE III et d'essais en simulation.

D'une manière générale, on peut dire que ces nouvelles commandes sont techniquement au point ou en passe de le devenir rapidement. L'expérience en vol a révélé que les conséquences de la position très couchée du pilote sur le confort et la psychologie étaient bénéfiques, contrairement aux craintes qu'on avait pu avoir. En revanche, l'aspect ergonomique du dialogue avec les systèmes demande encore beaucoup de travail de la part des équipes chargées de les adapter à l'utilisation opérationnelle.

C'est ainsi qu'on doit éviter un des travers classiques de l'informatique qui conduit à une surabondance d'informations présentées, ce qui est particulièrement fâcheux à bord d'un avion de chasse où les facultés intellectuelles du pilote décroissent notablement avec la difficulté de la mission. En revanche, un traitement judicieux de l'information accessible au système doit permettre de libérer le pilote de la plupart des analyses élémentaires, en ne lui laissant que les tâches nobles, comme le choix des options tactiques, pour lesquelles il est irremplaçable dans le contexte des opérations aériennes.

1. INTRODUCTION.

Sur les avions de la génération du MIRAGE 2000, l'informatisation est limitée au système d'armes; les données relatives au porteur restent classiquement acheminées par des réseaux câblés analogiques. En cabine, on retrouve une discrimination bien marquée entre les instruments relatifs au porteur et ceux consacrés au système d'armement et de navigation.

Désormais, un avion d'arme sera un ensemble informatique cohérent où chaque élément qui le constitue pourra avoir accès à l'ensemble des informations disponibles à bord. En cabine, on pourra procéder à une restructuration complète de l'architecture.

Nous allons voir que le démonstrateur RAFALE possède ces caractéristiques à un niveau déjà très élevé. La commande vocale avant d'y être implantée a fait l'objet d'essais étendus en simulation et en vol.

L'utilisation au cours de séances d'essais de ces systèmes nouveaux a été menée en gardant toujours à l'esprit la nature des contraintes qu'impose au pilote la mission opérationnelle. De ces expériences, nous pouvons tirer des enseignements. Nous verrons en particulier qu'un système techniquement au point ne suffit pas forcément à remplir une mission donnée s'il ne présente pas de surcroît une excellente adaptation aux caractéristiques humaines bien particulières d'un pilote de combat en cours de mission.

2. LES PRINCIPAUX SYSTEMES NOUVEAUX UTILISES.

2.1. Architecture de la cabine du RAFALE.

Les caractéristiques aérodynamiques en configuration d'atterrissage ou d'appontage, le choix du type de siège éjectable, et les exigences en matière de visibilité vers l'avant fixent à priori un nombre important de paramètres géométriques de la cabine. Cependant, l'angle d'inclinaison du siège, qui peut être pris dans une plage assez étendue, constitue le choix le plus déterminant dans l'architecture du poste de pilotage.

La résistance du pilote au facteur de charge dépend en particulier de l'angle que fait son dos avec le vecteur accélération. L'augmentation de cet angle s'accompagne de conséquences importantes sur l'organisation de la cabine: perte de l'accès physique à la majeure partie du tableau de bord, diminution de la surface de ce dernier, nécessité de piloter avec un manche latéral, perte de l'accès facile aux banquettes latérales. Hormis son domaine de fonctionnement à l'éjection, la limite de l'inclinaison du siége est fixée par l'apparition des genoux du pilote dans le champ visuel en approche. Dans ce cas, la surface du tableau de bord est évidemment annulée.

Le choix d'un angle supérieur à 30° qui a été retenu permet de conserver un tableau de bord capable de recevoir deux Visualisations Tête Basse (VTB) non accessibles à la main du pilote. Cette dernière caractéristique interdit de leur associer sur le pourtour des touches de désignation, comme on en trouve par exemple sur F 18.

Cet écran couleur tête basse peut présenter différentes pages concernant l'avion ou les systèmes. Le choix des pages peut se faire de différentes manières. On peut désigner une étiquette par une alidade pilotée par "joy stick", on peut faire défiler les pages grâce à un bouton poussoir, on peut appeler directement en cas de panne la page correspondant au circuit concerné, ou encore appeler les pages par commande vocale. Les pannes ou les anomalies sont annoncées par un Avertisseur d'Alarmes Vocal (AdAV).

Le "joy stick", piloté par le pouce gauche, fonctionne classiquement selon le principe d'une commande en vitesse.

Le Collimateur Tête Haute (CTH), monochrome à grand champ, présente un ensemble de réticules de pilotage directement dérivés de ceux du MIRAGE 2000. Le "joy stick" peut conduire l'alidade dans le champ de la VTH. On peut ainsi désigner certains réticules et les modifier.

Le Collimateur Tête Moyenne (CTM), également monochrome, constitue un prolongement continu du CTH. Il pourra ainsi, associé à un capteur TV ou FLIR, étendre vers le bas le champ de vision du pilote. Ce collimateur peut présenter comme la VTB différentes pages sélectionnées de manière semblable.

Sous le CTM, se trouve le Clavier Multiplexé (ClaM), placé incliné entre les genoux du pilote. Ce clavier devient le poste de commande de chacune des radios, du VOR ILS, des centrales à inertie lorsque partant de la page de base (le "menu"), on enfonce la touche correspondant à la fonction choisie.

Le manche latéral est à faibles débattements. Il comporte de nombreuses commandes dites "temps réel". Le manche et la manette sont conçus pour un pilotage selon le concept 3 M (Mains sur le Manche et la Manette) dans toutes les phases opérationnelles du vol. Les avant-bras du pilote reposent sur des accoudoirs réglables.

Une manette unique commande les deux moteurs. On peut éventuellement dissocier chaque moteur grâce à sa petite manette auxiliaire. Cette manette unique comporte sur sa surface un grand nombre de commandes "temps réel".

Sur les banquettes latérales se trouvent des commandes secondaires qui ne sont susceptibles d'être actionnées qu'au sol ou au cours de phases de vol stabilisées sans accélération.

Si le tableau de bord principal n'est pas accessible, il a été cependant possible d'aménager deux petites surfaces latérales que le pilote peut atteindre de la main. On y trouve principalement la commande de sécurité générale d'armement, la commande de manoeuvre du train d'atterrissage, des interrupteurs de secours de commande de vol, et le Poste de Modification de Paramètres (PMP).

Ce poste est constitué de deux couronnes concentriques. La couronne extérieure permet de sélectionner le paramètre à modifier (calage barométrique, but de navigation, canal radio), la couronne intérieure permet de faire varier le paramètre choisi. Le compte rendu de l'action est présenté sur la VTH. On évite ainsi, pour les modifications simples, une procédure plus lourde au clavier ou au "joy stick".

2.2 La commande vocale à mots isolés.

Après une phase d'essais en simulation, ce système avait été implanté sur un MIRAGE III R. Il comporte trois fonctions essentielles:

- Les annonces et les alarmes. Par exemple, "fin de transfert de voilure", "incidence trop forte", grâce au système de synthèse vocale.

- La réponse à des questions. Par exemple, "vitesse ?", "vitesse 430 Kt", grâce au système de reconnaissance et de synthèse vocale.

- L'action sur des ordres. Par exemple, "autocommande !", "autocommande embrayée", et embrayage de l'autocommande.

Ce système de reconnaissance monolocuteur possède un vocabulaire de 22 mots isolés avec des temps de réponse inférieurs à la seconde. L'ordre ou la question doivent être formulés après un appui bref sur un poussoir avant de prononcer le mot.

L'apprentissage s'effectue au sol. En vol, il est possible de réapprendre un mot régulièrement mal reconnu. La qualité de l'apprentissage est contrôlée par un test de reconnaissance.

Le système de reconnaissance vocale rend compte de ce qu'il a compris en répétant l'ordre ou la question. Pour certains ordres, une confirmation est nécessaire. Par exemple, le pilote demande "la tour !", le système répète "la tour", le pilote confirme "go !", et la fréquence de la tour de contrôle se sélectionne sur le poste et s'affiche sur le clavier de commande. En cas d'incompréhension, un des diagnostics suivants peut être retourné: "trop fort", "trop faible", "trop long", "répétez".

2.3 La commande vocale à mots enchaînés.

Ce système a été implanté sur le simulateur d'étude MIRAGE 2000. Il a été essayé dans le cadre d'une mission classique d'interception avec usage des différents armements et systèmes.

Il permet de commander:

- les fréquences des postes radio, du VOR ILS, du TACAN, du transpondeur,
- l'altitude à tenir par le pilote automatique,
- les modes du Système de Navigation et d'Armement (SNA),
- les fonctions du viseur,
- les échelles et les modes de fonctionnement du radar.

Il s'utilise par appui bref sur un poussoir de la poignée pilote précédant la phase de parole. Les fréquences ou les canaux des postes de radio ou de radio navigation doivent être épelés chiffre par chiffre.

Le vocabulaire est de 62 mots et de 51 chaînes.
Le retour vocal de l'ordre compris par la machine n'est pas systématique.

3. RESULTATS OBTENUS, COMMENTAIRES, EVOLUTIONS SOUHAITABLES.

3.0 A quoi sert le pilote ?

Il serait ambitieux de vouloir répondre complètement en quelques lignes à cette question, mais il n'est pas inutile de rappeler ici quelques points importants.

Dans une mission opérationnelle, les capacités intellectuelles d'un pilote décroissent d'autant plus que les conditions du vol sont difficiles: zone hostile, mauvaises conditions météorologiques, grande vitesse, basse altitude, vol de nuit...

L'intérêt majeur de la présence de l'élément humain à bord de l'avion réside dans sa capacité à s'adapter à la situation du moment, à effectuer des choix tactiques dans un contexte qui restait a priori grandement imprévisible avant le début de l'action elle-même.

On a donc deux réalités antagonistes. D'une part la puissance intellectuelle affaiblie du pilote, et d'autre part la nécessité pour lui d'analyser une situation complexe avant de procéder à des décisions tactiques qui peuvent souvent avoir des conséquences vitales. Il faut donc s'arranger pour que le peu de capacité d'analyse et de jugement qui reste au pilote soit exclusivement consacré à l'éxécution des opérations qu'il est seul à pouvoir accomplir.

Dans ce but, un avion moderne doit posséder deux caractéristiques fondamentales en ce qui concerne l'organisation de sa cabine:

- Automatisation très poussée de la gestion de l'avion et des systèmes par des logiciels "experts" capables d'effectuer les interprétations élémentaires.

- Présentation simple, selon des schémas proches des schémas mentaux humains, des éléments d'information dont le pilote aura besoin pour élaborer ses décisions.

3.1 Position de pilotage.

On a pu craindre que la position de pilotage très inclinée, qui ressemble à la position que l'on a dans une chaise longue, tendrait à émousser l'ardeur combative du pilote.

En réalité cette position entraîne une augmentation de confort très sensible, en particulier sous facteur de charge dont les effets néfastes sont nettement atténués. De ce fait le pilote n'appréhende pas les évolutions soutenues sous forte accélération. Il se sent naturellement protégé. Ainsi son agressivité, vertu cardinale chez un chasseur, s'en trouve au contraire consolidée.

Les avant-bras bien tenus par les accoudoirs réglables, associés à des lois de commandes bien adaptées, permettent un excellent dosage des gestes de pilotage. Ces derniers sont plus précis qu'avec un manche classique où l'avant-bras repose le plus souvent sur la cuisse droite, elle-même revêtue d'un pantalon anti-g qui se gonfle ou se dégonfle au gré du facteur de charge.

3.2 Désignation des étiquettes dans les visualisations.

La perte de l'accès physique à la majeure partie du tableau de bord interdit de disposer sur le pourtour des écrans de VTB des touches de désignation comme c'est le cas en particulier sur F 18 ou sur les FMS des avions de transport. Toutes les désignations d'étiquettes s'opèrent grâce au "joy stick" qu'on pilote du pouce gauche.

C'est une commande dite "en vitesse", c'est à dire qu'à un déplacement donné de la commande correspond une vitesse de déplacement de l'alidade. Celle-ci peut se mouvoir dans les trois visualisations. Elle saute d'une visualisation à l'autre lorsqu'elle atteint une limite d'écran.

Rappelons que la grande majorité des opérations possibles par "joy stick" l'est également par un autre moyen, PMP, clavier, tourne-page, interrogation sur panne, commande vocale.

On peut dire que le pilotage d'un réticule par une commande en vitesse n'est pas une nouveauté. On trouve ce système à bord des avions de combat depuis l'apparition des radars embarqués. Il n'en reste pas moins que ce geste de pilotage demande une certaine habileté de la part du manipulateur. D'autre part la désignation elle même, qui s'opère par appui sur le "joy stick", demande un geste bien vertical si on ne veut pas glisser sur l'étiquette d'à-côté.

Avec l'habitude, on ne se rend plus compte que ces opérations mobilisent tout de même une part non négligeable de l'attention. Ceci va dans le sens de l'accroissement de la charge de travail. C'est fâcheux.

Une commande en vitesse, même associée à des lois de déplacement très bien étudiées, ne se manipule pas aussi facilement qu'une commande dite "en position", où la position du réticule est asservie à celle de la commande. La manière naturelle de modifier la position d'un objet est bien de faire dans l'espace le geste qui correspond au déplacement souhaité. La "souris" des micro-ordinateurs est une commande de ce genre. Bien entendu on l'imagine mal directement adaptée à une cabine d'avion de combat. Mais il en existe d'autres modèles.

Par exemple la boule de désignation qu'on trouve souvent sur les consoles de contrôle de la circulation aérienne. Elle est unanimement reconnue comme un modèle de commande en position, d'emploi particulièrement aisé. On devrait pouvoir l'adapter aux cabines d'avions. Il faudrait pour cela concevoir une boule semblable, mais de taille réduite, qui pourrait être logée dans la tête d'une manette des gaz ou d'une poignée pilote dont la forme serait adaptée à l'usage de cet accessoire.

La mise au point d'une telle commande, qui remplacerait très avantageusement les "joy sticks", contribuerait à diminuer la charge de travail à bord des avions. Notons ici que son emploi pourrait s'étendre aux avions de tous types. Il y a là pour les industriels un effort technologique à faire. Il est digne d'intérêt.

3.3 Utilisation du clavier multiplexé.

Les postes de commande des différents équipements de radio, radio-navigation, ou de navigation à inertie sont habituellement disséminés dans la cabine. Ce clavier permet de les placer tous à l'endroit le plus accessible et le mieux en vue.

Cet avantage considérable se paie d'un inconvénient: il faut configurer le clavier avant d'accéder au poste de commande souhaité. Cet inconvénient peut être sérieux, voire rédhibitoire, si les logiques adoptées pour les touches sont mal étudiées. En effet, pour chaque poste de commande il existe plusieurs niveaux de sous-pages. Si par exemple on se trouve dans la dernière sous-page du poste de commande de navigation et qu'il faut très rapidement changer de fréquence radio, on doit pouvoir reconfigurer immédiatement le clavier en poste de commande radio. Or, en cours d'utilisation, la page de menu n'est plus présentée.

Cet inconvénient potentiel du ClaM peut être évité de deux manières. On peut faire un clavier plus grand avec une page de menu présentée en permanence, mais on prend alors plus de place en cabine, ce qui va à l'encontre d'un des buts recherchés. Ou bien on adopte une logique de touches telle que la procédure de reconfiguration puisse s'éxécuter par un geste mécanique du pilote sans demander la moindre réflexion de sa part. Sur le clavier du RAFALE, quelle que soit la configuration du clavier, un appui répété sur la touche supérieure gauche conduit dans tous les cas à la page menu.

Une autre difficulté vient des règles d'insertion. La question est de savoir si on doit insérer les paramètres par la touche appropriée ("insert" ou "enter"), ou bien si le paramètre doit être inséré automatiquement dès qu'il atteint un format qui correspond à ce qui est attendu. Par exemple pour entrer une route, disons la route 005, on peut adopter deux logiques: soit frapper 0-0-5 et le format à trois chiffres pour une route étant atteint la valeur est insérée, soit frapper 5 "insert". La même question se pose pour chaque paramètre pouvant être frappé sur le clavier.

Cette question n'est pas nouvelle. Elle s'est posée lors de la création des postes de commande de navigation. Les réponses qui lui ont été apportées n'ont d'ailleurs pas toujours été très heureuses. Leur antériorité ne justifie pas qu'on les reconduise sur les nouveaux avions. Aujourd'hui le dialogue alphanumérique s'étend considérablement. Il est impératif de standardiser et d'homogénéiser les procédures de dialogue par clavier. A ce propos on peut regretter que la disposition des touches des claviers embarqués soit différente de celle de toutes les calculettes du commerce (la ligne 1 2 3 est en haut au lieu d'être en bas). Voilà un cas où un automatisme quotidien aurait pu être exploité et ne l'a pas été.

Ces détails ne sont pas anecdotiques. Une accumulation de petites difficultés de dialogue dont aucune n'est rédhibitoire, peut finir par rendre les échanges lourds et pénibles, accaparant inutilement l'attention du pilote qui négligera donc la conduite de sa mission. Et en fin de compte les conséquences opérationnelles sont aussi graves que si les performances de l'avion ou du radar étaient insuffisantes.

3.4 Utilisation du Poste de Modification de Paramètres.

Cette commande d'aspect extérieur très simple, deux couronnes concentriques dont une seule graduée, très accessible, est un modèle de facilité d'utilisation. On s'y adapte instantanément.

Ce principe est à retenir. L'usage d'une telle commande doit être rendu possible pour la modification de tous les paramètres simples, qu'ils soient liés au porteur ou au système d'armes.

3.5 Présentation des informations

A partir du moment où l'information subit un traitement avant d'être présentée au pilote, ce traitement doit effectuer toutes les interprétations qu'il est possible de programmer.

Ce principe peut s'illustrer par un exemple. Sur RAFALE, lorsque les réservoirs de voilure sont presque vides, et que l'avion est en piqué accentué, le jaugeage indique "voilures vides" prématurément. En effet la quantité de carburant consommée correspondant à cette phase du transfert n'est pas encore atteinte. La page carburant présentée en VTB indique alors une anomalie de transfert voilure. On a là un traitement incomplet de l'information concernant le carburant qui n'apporte pas d'aide au pilote, puisque ce dernier doit tout de même se livrer à une interprétation. Cette anomalie, qui sera rapidement corrigée, montre que l'informatisation n'apporte une aide efficace que dans la mesure où elle est capable d'effectuer elle même les interprétations systématiques, et de les faire complètement.

Ces opérations concernent la sécurité de l'avion. C'est pourquoi la fiabilité de ces logiciels doit être compatible avec l'importance des tâches qui leur sont confiées.

L'alarme vocale apporte une aide considérable si elle est bien adaptée. Elle attire beaucoup l'attention, ce qui est une qualité, mais de ce fait on ne peut pas accepter les déclenchements intempestifs.

Comme le système est riche et puissant, il peut dire et écrire beaucoup de choses pour chaque cas de panne. La tendance des concepteurs est de donner beaucoup d'informations. Si cette information écrite sur les visualisations et énoncée par l'alarme vocale est trop abondante, présentée sans distinction entre ce qui est une annonce et ce qui est une consigne à appliquer, on se trouve dans une situation où une bonne partie des avantages du système est perdue à cause d'une présentation mal adaptée, peu rigoureuse, et pléthorique.

3.6 Commande vocale

L'utilisation en vol de la commande vocale associée à la parole synthétique (pour le système à mots isolés), ou même en simulation (pour le système à mots enchaînés), montre que cet outil n'est pas une panacée mais qu'il peut rendre de très grands services s'il est utilisé dans son domaine de pleine efficacité.

Pour la commande à mots isolés, on peut dire que la technique est au point, et que les taux de reconnaissance hors facteur de charge élevé sont satisfaisants pour des commandes non essentielles.

La reconnaissance est assez bonne pour des premiers vols. Néanmoins la prononciation de certains mots comme "vitesse" change sensiblement selon la phase de vol. Lors de l'apprentissage, période calme, le "e" final est plus marqué qu'en approche finale, période plus intense. C'est à ce moment où on a le plus besoin de l'information que la machine ne comprend plus.

Un des intérêts évidents de la commande vocale, auquel on pense d'emblée, est la fourniture d'informations, ou la sélection de fonctions d'armement, au cours du combat, sous facteur de charge, pendant que le regard reste fixé sur l'adversaire. Dans ce domaine, les résultats sont décevants. En effet, sous facteur de charge, si la compréhension reste à peu près constante jusque vers 4 g, elle se dégrade nettement au dessus. A 6 g, il faut plusieurs tentatives pour obtenir une compréhension après avoir essuyé plusieurs "moins fort" et "répétez".

Ce problème ne se rencontre pas pour les changements de fréquences radio ou de radio navigation qui ne s'effectuent en général pas sous facteur de charge élevé. Cette fonction est intéressante car elle effectue en plus un traitement de l'information. Elle traduit un ordre humanisé "LA TOUR", en valeur numérique "268.10".

Bien que le vocabulaire soit limité, il arrive que le pilote ait du mal à retrouver le mot correspondant à la fonction qu'il souhaite. En essais, il peut sortir son lexique. C'est alors une démonstration d'inefficacité. En opérations il devrait pouvoir utiliser des synonymes.

En ce qui concerne la commande à mots enchaînés telle qu'elle a été essayée en simulation, l'état de mise au point était beaucoup moins satisfaisant.

Le principe de base d'utilisation - appui bref sur la commande d'ouverture de micro, puis parole - ne correspond pas aux automatismes habituels acquis avec les radios de bord. Ce système conduit souvent à ne plus savoir où en est la reconnaissance, si on peut poursuivre la locution, si on doit reprendre à zéro, ou si on doit dire "effacez".

La modification qui autorise l'appui permanent a été greffée sur ce système mais ne constitue pas une véritable commande à appui permanent. En particulier, une interruption moyenne, (entre 0,2 et 2 s) est souvent suivie d'une incompréhension.

La reconnaissance est beaucoup plus mauvaise que pour les mots isolés. On bute par moments sur telle ou telle expression, puis cela s'arrange alors que la prononciation paraît constante. S'il y a des difficultés avec un mot donné, il faut réapprendre toutes les chaînes qui le contiennent.

On a rapidement vu les dangers d'un système sans compte-rendu systématique: en cas de confusion, on ne sait pas ce qu'a fait la commande. Ceci pourrait avoir de graves conséquences!

Le vocabulaire est à l'évidence trop étendu pour la capacité de mémoire d'un pilote en vol. Les séances se font le lexique à la main.

En particulier, l'affichage d'une fréquence V.O.R. en épelant chiffre par chiffre est une charge de travail nettement plus lourde qu'un affichage manuel. De plus, la prononciation des chiffres varie beaucoup suivant leur position dans la chaîne lors d'une prononciation courante; il faut donc adopter une prononciation très peu naturelle, ce qui est très pénalisant. En revanche si on pouvait dire "VOR NEVERS", il y aurait un bénéfice considérable. On retrouve là l'intérêt que présente la commande vocale si elle permet d'humaniser davantage la cabine.

Souvent, on ne trouve pas d'emblée la locution exacte pour obtenir un résultat, mais son synonyme. Par exemple on demande "viseur approche" ou bien "passer approche" pour "select approche".

Il faut réduire les actions possibles et utiliser la vaste capacité de mémoire pour l'emploi de synonymes.

4. CONCLUSION.

L'informatisation généralisée des avions de combat rend possible des architectures de cabine et des systèmes de commande radicalement nouveaux.

Dans ces interfaces nouvelles, l'information qui est échangée entre le pilote et la machine peut subir des traitements et prendre des formes extrêmement variés.

Le champ possible de ces traitements et de ces formes est presque illimité techniquement.

L'expérience de l'utilisation de certains de ces éléments, écrans, claviers, commande vocale, montre que c'est l'adaptation ergonomique, au sens physique et surtout mental qui manque le plus souvent de mise au point.

Il faut en conclure que les travaux à venir devront faire appel pour une très large part aux avis des principaux intéressés, les pilotes. De leur côté, ces derniers devront faire l'effort d'analyser rigoureusement ce qu'est leur comportement, et ce dont ils ont besoin au cours d'une mission opérationnelle. De cette analyse devraient découler les éléments dont ont besoin les constructeurs pour donner aux échanges entre le pilote et son avion des formes bien appropriées.

DESIGN CONSIDERATIONS
for
VIRTUAL PANORAMIC DISPLAY (VPD) HELMET SYSTEMS

by

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SUMMARY

This paper describes some of the fundamental performance and design parameters that should be considered for the successful evolution and integration of a new type of helmet mounted display (HMD) system intended for use in military aircraft cockpits/simulators. It is called a virtual panoramic display (VPD). The parameters discussed include field-of-view (FOV), exit pupil, image quality, eye relief, collimation, alignment, size, weight, system integration issues, and several others. For the *first time the associated helmet system* is considered as an integral subsystem that must be designed to support the requirements of the HMD. Trade-offs relating to the intended VPD applications (i.e., cockpit simulators/rotary wing aircraft), HMD design and its impact on the associated image source and display electronics are discussed. Design issues and considerations *are developed primarily from the* viewpoint of the VPD system integrator.

INTRODUCTION

A virtual panoramic display (VPD) is a subset of helmet-mounted display systems (systems being a key word) that provides the pilot or operator with a large instantaneous field-of-view, whose displayed information has been organized both temporally and spatially to maximize the effectiveness of the man/machine interface and, *therefore, maximize operational/situation awareness* [05]. The VPD system concept seeks to optimize its electronic interfaces with the aircraft or simulator system and the human's cognitive and sensory systems. The concept becomes an application-specific design problem involving not only the VPD hardware itself, but the design and operational specifications of *all* other hardware subsystems with which it must be interfaced. In this paper, discussion will include only the VPD visual subsystem hardware whose major components are outlined by the heavy dotted line in Figure 1.

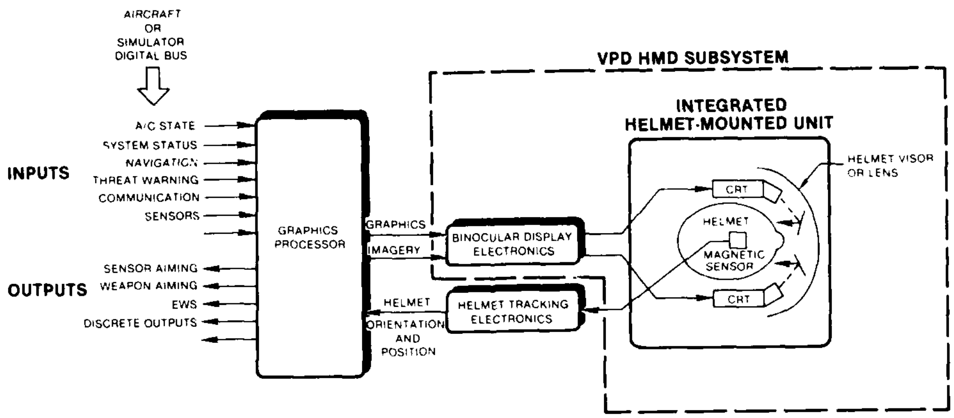


FIGURE 1
GENERIC VPD SYSTEM HARDWARE BLOCK DIAGRAM

The VPD visual subsystem includes a binocular display whose visual fields are either fully or partially overlapped, permitting, if desired, the presentation of stereoscopic images. The binocular optics are driven by miniature cathode-ray-tubes (CRTs) *of an advanced design.* The optics and CRTs are integrated into a custom helmet system. The CRTs are interfaced to specially designed analog helmet-mounted display electronics which "tailor" the displayed information to the requirements of both the optical and CRT design. The analog display electronics accepts inputs from both external system sensors and computer-generated graphics systems, as well as a VPD graphics processor that supplies application specific, customized, interactive symbology and graphics. The VPD graphics processor may or may not be present in a given VPD system configuration. Because the graphics processor's impact on the helmet system components is minimal, its functions will not be discussed further.

As shown in Figure 2, the head mounted CRTs must image their visual information through a set of relay optics, which may use fiber optics and/or conventional refractive elements/prisms/mirrors. A combiner or combiner/beamsplitter arrangement that may or may not be part of the helmet visor, reflects light from the CRT and transmits the outside scene. The CRTs and optics are part of an integrated helmet system (IHS) that maximizes optical system stability/functionality on the head, minimizes modifications to the helmet/head weight and center-of-gravity (CG), and protects the wearer from

hostile ambient environments. To accomplish these functions, the IHS design must use advanced materials and structures, and optimize adjustment and alignment hardware and earphone/microphone/oxygen mask components.

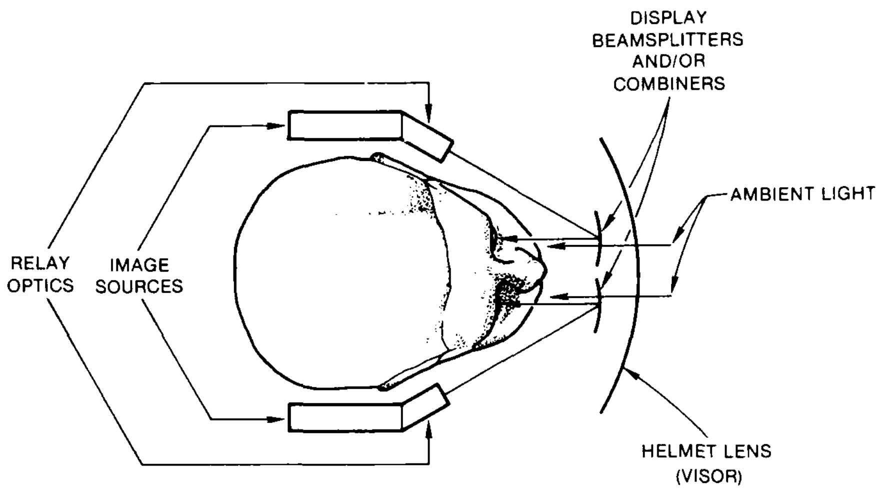


FIGURE 2
VPD HEAD/VISUAL SYSTEM RELATIONSHIPS

This paper is concerned primarily with simulator and rotary wing aircraft applications, and therefore, the breadth of discussion is somewhat specialized, although much can be inferred concerning the design of such systems for other types of aircraft. Before discussing design considerations, it is worth noting why a binocular head mounted display system was selected, instead of a cockpit mounted system, where weight/size limitations are not nearly as severe. As Figure 3 shows, there are a number of design alternatives for a wide FOV cockpit display system. A major goal of the VPD was to maximize situation awareness regardless of the operator's line-of-sight (LOS). This can be accomplished either with a reduced instantaneous FOV display that is head mounted and updated rapidly, based upon head orientation and position, or with an extremely large instantaneous FOV display that is cockpit-mounted.

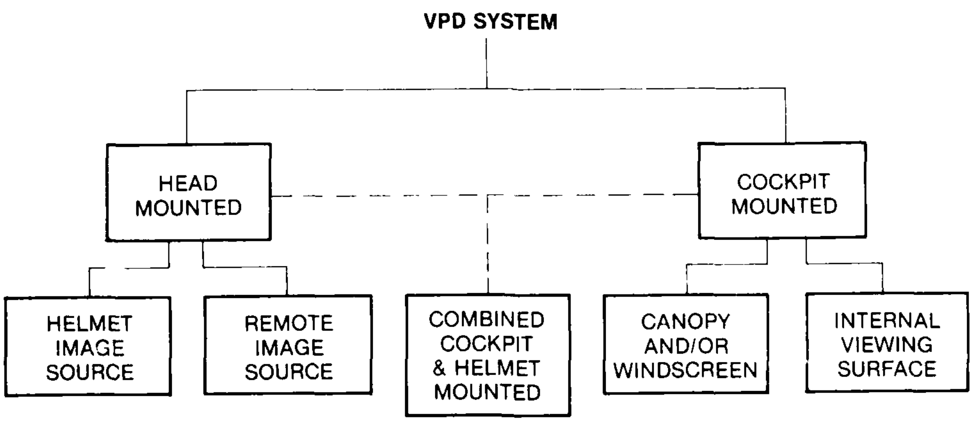


FIGURE 3
VPD DESIGN ALTERNATIVES

The choice between these major design alternatives was limited by a number of performance and technology issues. During the early design stages of the VPD program, it was decided that stereoscopic cues (using visual disparity between the two eyes) might aid the operator in ordering the relative importance of critical display information. From either a cost or performance viewpoint, current technology does not permit construction of either a cockpit-mounted or a combination cockpit/head mounted system providing the above features, therefore these were eliminated from consideration. Further, a wide FOV head-mounted display system utilizing a remote image source, coupled to the head,

using either re ractive or fiber optic image conduits, suffers from a number of severe design problems, including red: ced display resolution/contrast, the possibility of excessively rigid and heavy optical conduits bet.een the head and cockpit, and stray light. Therefore, a display configuration including head mour:ed optics and image sources is the only alternative considered here. The reader should also note that, for the remainder of this paper, the term helmet mounted display (HMD) will be used interchangeably with VPD when referring to the helmet mounted components.

VPD DESIGN CONSIDERATIONS

OPTICS

Textbooks and engineering handbooks list many design parameters and attempt to specify and organize design parameters associated with optical systems, including helmet mounted displays (HMDs). Table 1 depicts a representative list of parameters and generalized numerical figures-of-merit (FOM) for each parameter. However, HMD design is tightly coupled to the intended application, and the use of a generalized table of parameter values or generalized design approach will not usually lead to satisfactory results. The relevant technical literature also provides scant help, and there are many large gaps in applied research that, if available, might provide for better organization of the design approach. One must, then, gather as much information as possible about the intended application and system interfaces, and hope that the available technology will support the development of an adequate design.

TABLE 1
HMD OPTICAL SYSTEM DESIGN PARAMETERS

QUANTITY	TYPICAL RANGE	TOLERANCE
FIELD-OF-VIEW (INSTANTANEOUS)	70° TO 120° HOR × 30° TO 60° VER	NA
PUPIL SIZE		
HELMET MOUNTED	10 TO 23 MM	± 1
EYE RELIEF		
HELMET MOUNTED	35 TO 45 MM	± 3
FOCAL LENGTH	10 TO 30 MM	NA
f-NUMBER	0.7 TO 2.0	± .2
CONTRAST RATIO (APPARENT)	0.2 TO 0.80	± 0.1
DISTORTION	0.2 TO 5%	± 1
ASTIGMATISM	0.1 TO 1 DIOPTER	± .1
CHROMATIC ABERRATION	1 TO 6 ARC MIN	± 1
COLOR	B/W TO FULL COLOR	NA
CONVERGENCE	1 TO 30 ARC MIN	± 1
DIVERGENCE	1 TO 3 ARC MIN	± 1
DIPVERGENCE	1 TO 15 ARC MIN	± 3
DISPLAY REFRESH	60 TO 240 FIELDS/SEC	NA

To proceed with the necessary system analysis, which organizes the relationship of the available technology to the requirements of a specific application, one must arrange the parameters listed in Table 1 in order of importance. Due to the lack of definitive guidelines, this ordering is often based upon experience with current similar systems. However, the choices are complex, because of the various possibilities of constraining the types of displayed information for a given set of environmental conditions, and then mixing/matching display components to support those constraints. An example of such a scenario, of which there are many, is as follows:

a) Require that, during the high ambient luminance of daylight VPD operation, the display be limited to portraying vector graphic stroke information. It can be refreshed at higher rates and at wider line widths than raster information, to obtain maximum luminance contrast. This stroke-written information is then overlayed on the ambient scene background using a see-through display combiner.

b) During night or low ambient luminance conditions, permit the display of sensor or computer generated raster information with adequate contrast at lower maximum luminance levels. The normal ambient scene would then be replaced with a sensor-produced reproduction.

The underlying issue of this example is that display contrast, and therefore, the human operator's ability to see/use the information being delivered to him either day or night can be considered as one choice for the most important design parameter. This contrast parameter, then, drives all others in system designs that are ultimately evolved and built.

Figure 4 depicts the principle design categories of optical systems that might be ex loited to implement a collimated optical design suitable for use in a VPD. These categories are delineated by the system's primary basic operating principle, realizing that a particular design will combine more

than one principle to maximize performance. For the VPD systems covered in this paper, only system types 1 through 4 were finally considered for hardware implementation.

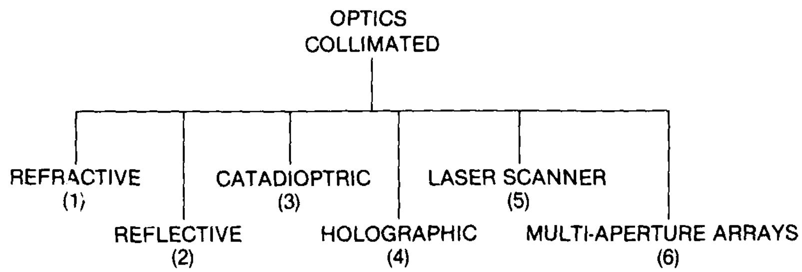


FIGURE 4
MAJOR DESIGN ALTERNATIVES FOR COLLIMATED HMDs

The design process is extensively modified, however, by the display hardware system's operating modalities. These might range from a system that must perform throughout the range of ambient conditions, to a design that will permit alteration of some of its components to match its performance to the extremes of the operating environment. Two separate designs, meant to accommodate separate portions of the environmental parameter ranges might also be reasonable. Given the many varied operational configurations for the VPD, only the more significant configurations and their associated performance are discussed in this paper.

Table 2 lists the systems and approximate values for some of the more important characteristics of each of the VPD HMD optical designs, for which working helmet system breadboards were fabricated. System 1 using a special version of the Farrand Pancake Window, employs a unique combiner design to obtain extremely large instantaneous FOVs, albeit at the extreme sacrifice of light transmission efficiency. Systems 2 and 3 are catadioptric systems using a combiner/beamsplitter combination to obtain large FOVs with reduced weight and improved, but still low, light transmission efficiency. Systems 4 and 5 are essentially refractive optical systems, using either a holographic or aspheric combiner mirror, that can provide very good light transmission efficiency, but with increased weight for FOVs comparable to systems 2 and 3. This summary is presented here so that the reader may be familiar with and reference this table as the VPD design considerations are enumerated and explained throughout the remainder of this paper.

TABLE 2
VPD HMD OPTICAL SYSTEM CHARACTERISTICS SUMMARY

CHARACTERISTICS	SYSTEM 1 FARRAND PANCAKE WINDOW	SYSTEM 2 O.D.S. CATA-DIOPTRIC	SYSTEM 3 FARRAND DUAL MIRROR	SYSTEM 4 HUGHES HOLO-GRAPHIC	SYSTEM 5 FARRAND OFF-APERTURE
EXIT PUPIL (mm)	19	21	15	15H × 10V	17/15
MONO. FOV (DEG)	80H × 60V	53H × 40V	60H × 45V	60H × 30V	50H × 37.5V
TOTAL HOR. FOV (DEG)	120	76	90	80	70
OVERLAP (DEG)	40	30	30	40	30
EYE RELIEF (mm)	39	72	32	90	60
POLYCHROMATIC	NO	NO	YES	NO	NO
CRT TO EYE TRANSMISSION	0.01C_r	0.25C_r	0.06C_r	0.85C_r	0.9C_r
SEE-THROUGH TRANSMISSION	0.08C_t	0.5C_t	0.5C_t	C_t	C_t
APPROX. WEIGHT OF OPTICS ASSEM. (gm)	490/LEG	250/LEG	210/LEG	350/LEG	460/LEG
INPUT FORMAT HOR. (mm)	19	16	19	19	16
EFL (mm)	13.6	16.9	18.1	18.1	17.2

C_r = COMBINER REFLECTANCE

C_t = COMBINER TRANSMISSION

SIZE OF FIELD-OF-VIEW (FOV)

Selecting this parameter is often the single most important decision that the system designer or integrator must make. It can have a major impact on the maximum obtainable display combiner contrast

for a desired ambient transmission condition. Large FOVs mean more head-supported weight, and unacceptable modification of the military headgear center-of-gravity (CG), less light transmission efficiency from the image-source-to-eye (ISTE), and, ultimately, more severe performance requirements for the image source and its associated display electronics. Designers must usually place greatest weight on the primary application for the system. If the display system is intended for ground-based use in simulators or other similar functions, then the designer may opt for the largest practical FOV. Large FOVs create a panoramic visual input and a feeling of being immersed in the environment or situation being depicted. However, operational field use, particularly military cockpits, places a premium on low weight, compactness, maintenance of vision to the ambient background under all head movement and aircraft acceleration conditions, usable contrast for both the displayed and ambient visual stimulus, and survivability in hostile environments. These considerations drive HMD designs toward smaller FOVs.

Figure 5 depicts the total instantaneous FOV for the human binocular visual system, over which the instantaneous display FOV for one of the largest binocular HMDs ever built, has been drawn. It is immediately apparent that the instantaneous display FOV (120 degrees horizontal by 60 degrees vertical) is much smaller than that for unaided eyes, yet the display system needed to achieve such performance is already too heavy for general use in operational rotary wing aircraft. It also suffers from very low ISTE transmission efficiency, and thus either very poor see-through capability, and/or very low CRT contrast. In additional, the monoculars have been turned out, allowing only the overlapping central forty degrees of horizontal FOV to be seen by both eyes. This places severe constraints on both the use of the optical design [01,20] and image source performance [18].

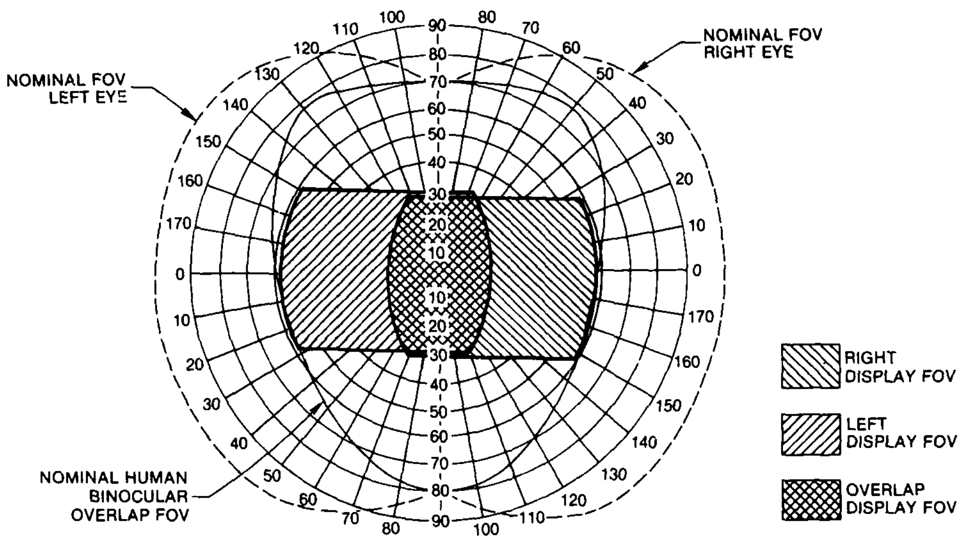


FIGURE 5
RELATIONSHIP OF HMD/EYE FOV

Binocular optical designs, particularly those employing partial overlap of their monocular FOVs, demand compatible mapping schemes for the display system's resolution elements across their angular FOVs [20]. For VPD optical designs, this usually means that F-theta mapping is the preferred mapping scheme (where the angular distribution of resolution elements becomes uniform), rather than F-tangent theta or even F-sine theta mapping (where there are excess angular resolution elements at the edges of the field). For partially overlapped systems, F-theta mapping offers the only practical solution to matching resolution elements for the same object at the edge of one eye/display monocular field to those that will be at an alternate, interior location to the field for the other eye/display monocular viewing the same object. F-theta mapping also eases the difficulty of the optical design process, allowing larger exit pupil sizes to be obtained for a given FOV [02,03]. If a full overlap condition is used, it might be desirable to introduce spline distortion. For this type of mapping, more of the resolution elements are located in the center of the display FOV than on the edge, thus approximating more closely, the foveal/peripheral topology of the eye's resolution.

For the conditions shown in Figure 5, the inboard -40 degree off-axis location for the right eye monocular, represents the 0.0 degree location on the left eye monocular. The implication of this fact for the image source, is that off-axis performance must be very similar to on-axis performance, as the central viewing portion of the display represents an off-center viewing location on the CRT, as shown in Figure 6. Further, to properly align the display formats for the eyes, as well as compensate for residual optical distortion, the CRT image source, must have its imagery predistorted to obtain proper perspective and overlay of the left and right eye display images. This is one reason why CRTs are the image source of choice over solid state image sources, because their resolution can be altered or mapped and is not constrained to the fixed patterns, positions and sizes of solid state image source

resolution elements. Display resolution and addressability issues relating to the use of HMDs in vibrating environments, may also be used as part of the total system analysis, but these considerations play a much more important role in vertical FOV selection.

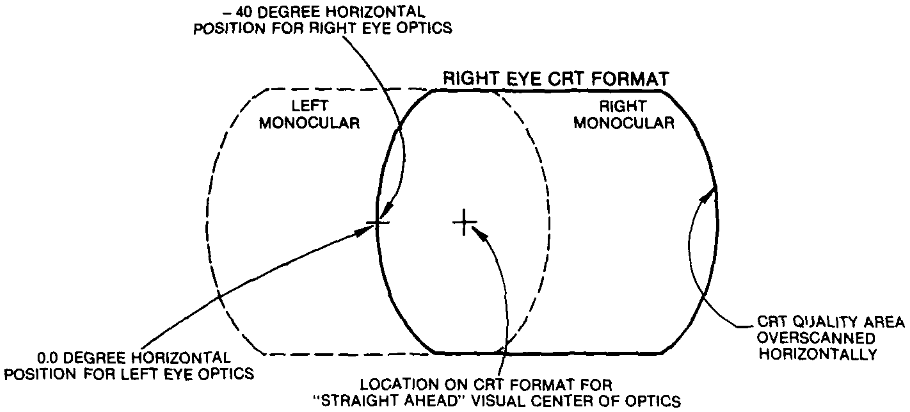


FIGURE 6
CRT FORMAT FOR PARTIALLY OVERLAPPED WIDE FOV OPTICAL DESIGN

Another important circumstance, affecting FOV selection, is the frequently levied requirement to have the sensor's FOV displayed in a direct 1-1 mapping on the HMD FOV. An example, is a FLIR system with a 50 degree horizontal by 37.5 degree vertical FOV, which must have the same apparent FOV when presented on the HMD. A requirement of this type for a panel mounted presentation would clearly be waived, because the resulting cockpit mounted display would be unacceptably large. Such a design requirement is feasible for the HMD which can have an angular subtense to the eye (apparent FOV) this large [22]. Further, if the display of more than one sensor input is required, and their associated FOVs are quite different, but their scan formats are similar, as is usually the case, then a primary sensor (normally the one used for pilotage tasks) must be chosen. The display FOV is then selected to accommodate 1-1 mapping of the primary sensor's FOV. Display magnification (or minification) must usually be accepted in analog systems, for the display of other sensors' information, because the dynamic range of the image source cannot usually support 1-1 mapping of all sensor presentations.

Having accepted this criteria, one must determine its impact. Setting aside, for the moment, sensor/display system design issues, the major design considerations become the scanning format, the number of pixel elements spread over the HMD FOV, and the scan format/pixel rate capability of the image source. A hypothetical set of sensor/HMD conditions is depicted in Figures 7a and 7b. In this example, a 4:3 aspect, 50 x 37.5 degree sensor FOV, with 750 visible scan lines and approximately square pixels, is to be presented using a 1-1 mapping of sensor-to-display resolution elements on the HMD. Assuming nighttime utilization of this sensor format and a see-through combiner, then the image source can be run at modest luminance conditions. For these conditions miniature CRTs can achieve 500 cycle (1000 pixels) per display width. Since the example sensor is providing 1000 pixels per line for simultaneous display, its format and the capabilities of the CRT image source dictate the mapping of resolution elements and ultimately the conditions for maximum HMD FOV. The two example conditions are diagrammed in Figure 7.

For the conditions shown in both 7a and 7b, the mapping of resolution elements reflects that of the sensor, while the overlap condition and the total number of sensor pixels displayed by the right and left eye image sources, has been changed to achieve different binocular horizontal FOVs for the HMD. Area ABCD for both figures indicates the entire binocular FOV that the CRT's addressability/resolution performance can support, given the requirement for 1-1 mapping of the sensor FOV onto the HMD FOV. Area WXYZ represents possible overlap conditions that the HMD CRTs can support for the given total sensor resolution and the total/overlap FOVs for the HMD. Areas RWZU and XSTY represent the remainder of the sensor presentation, which can be seen by only the right or left eye. Areas ARUD and SBCT represent the remaining display FOV, which the CRT's resolution/addressability performance can support for the stated drive conditions.

In those portions of the instantaneous display FOV, where sensor information is not displayed, additional peripheral motion/reference cues, such as artificial horizon lines, heading tapes, etc., might be drawn during the video vertical retrace interval, if vector graphic stroke symbology capability is present. Which FOV condition is designed into the HMD is application-dependent, although the preponderance of the sparse human factors data on this topic seems to indicate that maximum performance benefits occur at 50-60 degrees, increasing at a much reduced rate for still larger FOVs [13].

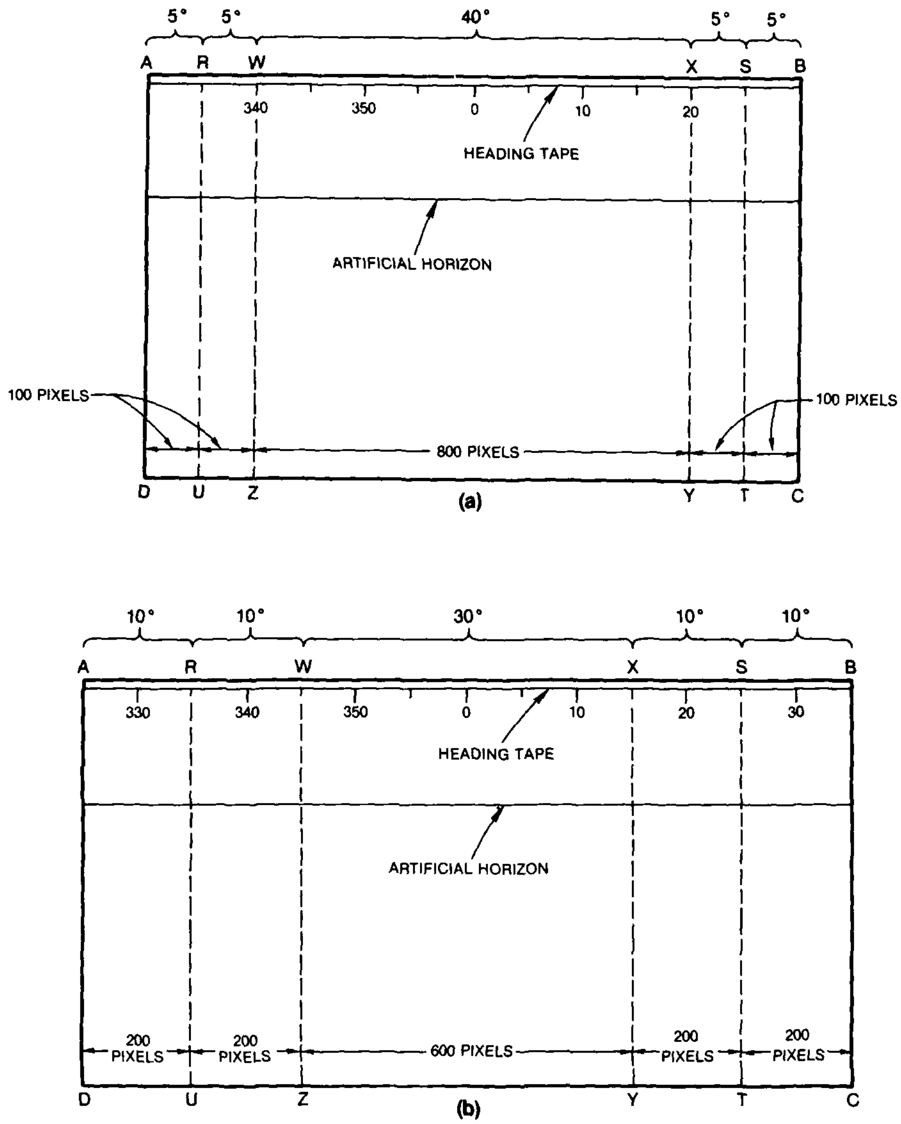


FIGURE 7
SCAN FORMAT RELATIONSHIPS FOR HYPOTHETICAL SENSOR/HMD COMBINATION

A complementary approach to establishing horizontal FOV allowing direct analytical calculation is to base the FOV determination on the overall system resolution [16]. The relationship shown in equation 1, relates resolution performance of the miniature CRT image source and the addressable resolution elements available from a given imaging sensor. These relationships may be combined to calculate the desired horizontal FOV for 1-1 mapping of the sensor FOV on the HMD. Using equation 1 and the assumed CRT/sensor performance, the desired horizontal FOV of the sensor display is 50 degrees.

Completing the determination of the maximum display binocular FOV, then reduces to computing the amount of binocular overlap that is attainable. This can be computed using the relationship shown in equation 2 [16]. Using equation 2, one computes an overlap FOV of 40 degrees. The computed horizontal and overlap FOV conditions, using both relationships, conveniently results in a format very similar to that diagrammed in Figure 7a. Of course, a mixture of the two approaches and widely dissimilar system conditions, might be combined to yield significantly different results.

$$\text{HOR FOV (DEG)} = \frac{\text{CRT FORMAT SIZE (mm)} \times \text{CRT RESOLUTION (lp/mm)}}{\text{17.5 (mrad/DEG)} \times \text{SENSOR RESOLUTION (lp/mrad)}} \qquad (1)$$

WHERE: ASSUMED
CRT SPOT SIZE = 19.0 MICRONS (0.019 MILLIMETERS) OR
26 LINE PAIRS PER MILLIMETER (lp/mm)

ASSUMED
CRT FORMAT SIZE = 19.0 MILLIMETERS

ASSUMED
SENSOR RESOLUTION = 0.57 LINE PAIRS/MILLIRADIAN (lp/mrad)

$$\text{BINOCULAR FOV OVERLAP (DEG)} = 2 \times \text{ARCTAN} \frac{\text{EYE SEPARATION (mm)}}{2 \times \text{EYE RELIEF (mm)}} \qquad (2)$$

WHERE: NOMINAL EYE
SEPARATION = 65 MILLIMETERS (mm) GIVEN 58-72 (mm)
OF NOMINAL ADJUSTMENT

Having an approach for determining the vertical FOV is also important, especially since human anatomical factors make vertical FOV more difficult to obtain for pupil-forming HMD systems [01]. Nominally, the monocular FOV will have a 4:3 aspect ratio, whose vertical FOV will be determined by its horizontal FOV and overlap condition, even though the total binocular presentation will differ significantly from such an aspect ratio. However, it is important to consider certain other closely related technical factors whose origins are partially in the psychovisual domain and partially in the system designer's domain. The psychovisual considerations pertain most importantly to the required size of the subtended angle of display resolution elements to the eye when such imagery is viewed in a vibrating environment [06]. The basic assumption is that the vertical vibration component (normally having an orientation approximately perpendicular to the HMD scan lines), is the largest and most important component [06]. Here, the literature relating to the viewing of HMDs, during vibration suggests that scan lines should subtend an angle to the eye of 2 to 4 arc minutes. This statement must be viewed with caution, since observer angular resolution is dependent on a number of interrelated factors, such as display luminance and contrast which are not always specified with the data. In addition, display operating conditions normally require that CRT scan line width be adjusted so that the scan line structure is not visible. However, sufficient dynamic range should be permitted between the minimum and maximum luminance levels, such that usable contrast is maintained between adjacent pixels imaged at different luminance levels on adjacent scan lines. To accomplish this goal, the display system designer needs to establish an acceptable scan line merge condition as shown in Figure 8. The merge condition selected should allow a reasonable tradeoff of scan structure contrast and vibration induced artifacts which affect visibility of the scanned image.

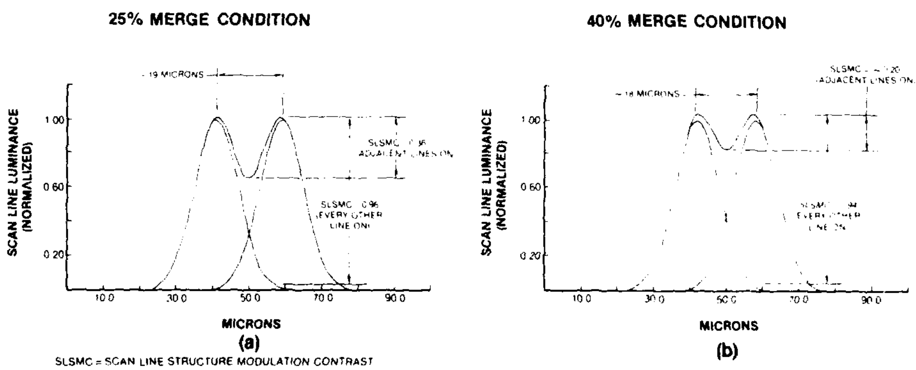


FIGURE 8
IMPACT OF MERGE POINT SELECTION FOR ADJACENT SCAN LINES

The CRT beam width conditions depicted are 12 - 14 microns at the 50 percent response point. At night, display of sensor imagery at this condition is easily supported by current miniature CRTs. Given the previous example condition of 750 visible scan lines, the distance between scan lines has been adjusted to 18 - 19 microns. This allows scan lines to subtend about 3 arc minutes of v . .1 angle for the 37.5 degree vertical FOV of the example HMD, which falls right between the 2 - 4 arc

minute requirement suggested in the literature. Ideal gaussian response is portrayed, although, for some miniature CRTs, the tails of each spot profile may, at certain CRT drive conditions, extend out to greater distances than indicated here [08]. When adjusting CRT performance and HMD FOV to match or preserve most of the initial sensor performance, the designer usually wants to insure that the scan line widths and merge conditions are adjusted to achieve minimum scan line structure modulation contrast (SLSMC), when adjacent pixels on *adjacent scan* lines are at peak luminance. Conversely, maximum modulation contrast is desired between adjacent scan lines, when every other scan line is at peak luminance levels and the adjacent pixels on adjacent scan lines are at their minimum luminance level. These relationships are shown, for two separate merge conditions in Figures 8a and 8b. A reasonable design procedure is to select a FOV and merge condition where, with adjacent scan lines at full luminance levels, the SLSMC is kept below the human operator's visual demand threshold for the modulation contrast/resolution conditions obtainable from the system [see reference 23, (Figure 29)]. It should be obvious that the 40 percent merge condition represented by Figure 8 comes closest to meeting the stated criteria.

Finally, something must be said about attempting to predict the relationship between total anticipated weight for the HMD optics and FOV. One predictor, sometimes employed for this purpose, is the Lagrange invariant [02] given by equation 3. It expresses a relationship for a constant level of

$$\text{LAGRANGE INVARIANT} = Q = (\text{EXIT PUPIL SIZE}/2)(\text{FIELD ANGLE}/2) \qquad (3)$$

complexity, as FOV is reduced from some defined maximum, to obtain an estimate of the reduction in the complexity of the number of HMD optical elements needed in a specific design. However, many other factors affect this relationship, such as the basic optical design, inclusion of polychromatic versus monochromatic performance, image source format size, and materials, used in the design and fabrication of an HMD. Thus, any useful general purpose relationship is difficult to formulate, although, for a specific design restrained to the same conditions, equation 3 can provide useful predictive benchmarks.

DISPLAY OVERLAP FOV

Among persons involved in the use and development of binocular HMD systems there is much controversy about the amount of display overlap to use between the monoculars. Figure 5 depicts a 40 degree overlap condition for monoculars, with an 80 degree horizontal FOV, or a 50 percent overlap condition. The approximate theoretical maximum for the eyes is 60 degrees. This condition might be obtained with certain HMD designs if the total FOV, exit pupil, and eye relief conditions were optimized to support it. However, helmet slippage on the head, the requirement for eyeglass compatibity, and therefore greater eye relief, etc. make it difficult to obtain. Experience with the Farrand Pancake Window simulator display system developed for the Visually Coupled Airborne System Simulator (VCASS) facility, which can be adjusted for fixed overlap conditions of 20, 40, and 60 degrees, has provided subjective indications that a display system with more overlap provides a more pleasing *panoramic display*. Recent, but not yet published experiments conducted by the Army Night Vision Laboratory with narrower FOV HMDs seem to suggest similar findings. However, no definitive study exists on this topic. As a minimum guideline, it can be stated that, with narrow FOV systems (those with monoculars having a horizontal FOV less than or equal to 40 degrees), a full overlap condition is desirable and, for larger FOV HMDs at least 30, and probably 40 degrees of overlap is desirable.

EXIT PUPIL SIZE

The exit pupil of an optical system that has one, is a disc to which all of the light from the system converges and from which it diverges, all of the light available to the eye. When the eye pupil is entirely within the exit pupil all portions of the HMD FOV may be viewed instantaneously and at the maximum brightness that the system can provide. The definitions one usually reads in optical texts to define exit pupil are usually for conventional telescopes and microscopes, where the entering light rays are nearly parallel and close to the optical axis. For these designs, the aperture stop, and therefore the exit pupil, is usually easily defined and explained. However, the design constraints for HMDs require that a relatively large object (the CRT phosphor) be viewed from a short object distance, while still providing a combination of large visual angle, large exit pupil size and enough eye relief to accommodate eye glasses. The relatively large CRT format, being close to the relay optics lenses, produces light rays that enter the optical system at large angles from the extreme off-axis points of the CRT format. The HMD optics aperture stop may be a combination of stops in the system and is not easily determined. It is usually left to the optical designer to define it and insure that it is obtained for the desired eye relief and FOV. However, the system designer must supply a reasonable justification for the desired exit pupil size based upon the anticipated luminance conditions, expected pupil sizes for the human eye, the anticipated quality and stability of the helmet system design into which the optics will be integrated, expected environmental conditions during operational use, and the realities of the optical design and weight penalties *associated* with increased exit pupil diameters. It should be noted that pupil size, as described in this paper, means the cross sectional dimension over which no vignetting of the HMD light occurs.

Figure 9 shows a simplified diagram of the human eye, taken from the Military Handbook of Optics (MIL-HDBK-141) with certain optical constants included, which can be used to obtain a first order cut at calculating the required exit pupil size. For this analysis, the entrance pupil of the eye has been assumed to be physically approximately 3.0 millimeters behind the cornea. The optical distance from the cornea to eye pupil is the physical distance divided by the index of refraction (3.05/1.337), of the aqueous humor, which is 2.25 millimeters. This is about the location, where HMD optical designers like to design for the exit pupil of the optics to be located. The center of rotation of the eye is approximately 13 millimeters behind the cornea, and thus the rotation center of the eye is 10 (13-3) millimeters behind the eye pupil, not at the pupil.

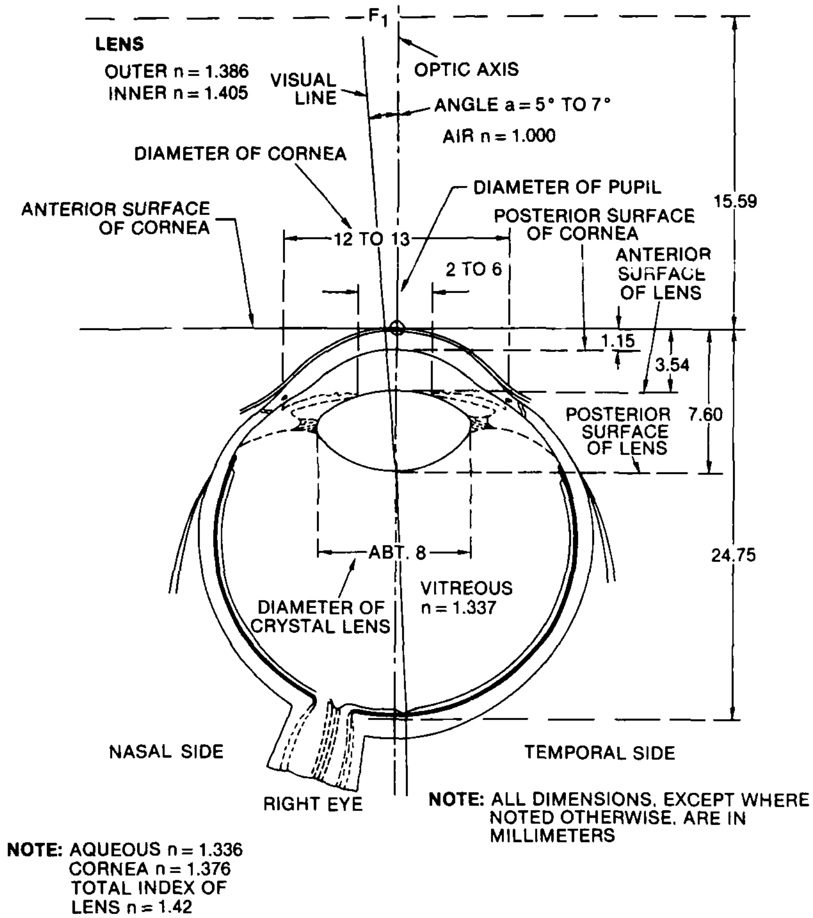


FIGURE 9
OPTICAL CONSTANTS FOR A "STANDARD EYE"

Figure 10 depicts the essential relationships needed to calculate eye pupil movement, as the eye is rotated to view off axis portions of the HMD FOV. Although eye pupil diameter can vary from 2 - 7 millimeters, depending upon display/ambient luminance conditions, the calculations were performed for eye pupil sizes of 2 and 5 millimeters, which is representative of variations that might be observed in a rotary wing aircraft HMD application. Using the dimensions and relationships shown in Figures 9 and 10, equation 4 can be derived.

$$\text{EYE PUPIL EDGE HEIGHT} = h = \frac{r[\sin(w+v)]}{\cos v} \qquad (4)$$

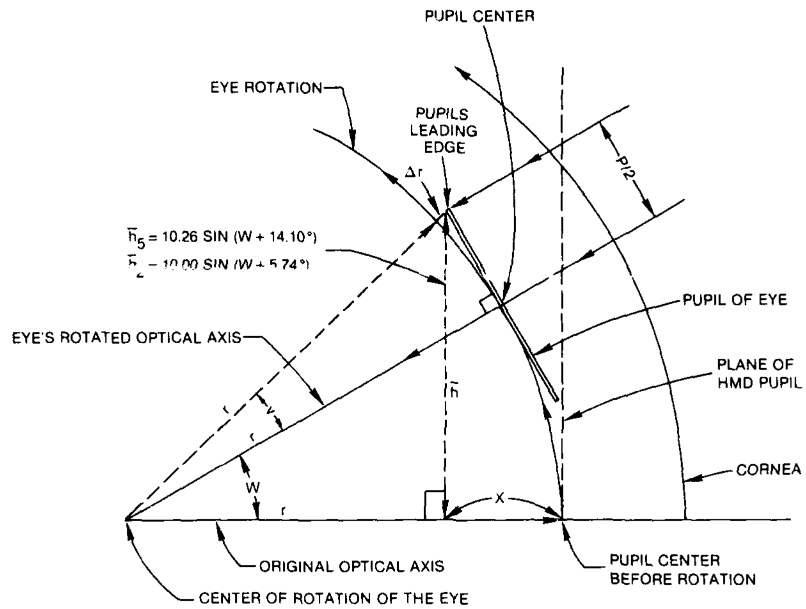
WHERE: $\cos v = r/(r+\Delta r)$, SO $(r+\Delta r) = r/\cos v$
AND $\sin(w+v) = h/(r+\Delta r)$

For the 2 and 5 millimeter eye pupil diameters, equation 4 reduces to

$$h_2 = 10.00[\sin(w + 5.739°)]$$

and

$$h_5 = 10.26[\sin(w + 14.10°)]$$



r = RADIUS OF ROTATION

P/2 = EYE PUPIL RADIUS

V = ANGLE SUBTENDED BY EYE PUPIL RADIUS

W = ANGULAR ROTATION OF EYE

$\bar{h}$ = ABOVE AXIS HEIGHT OF EYE PUPIL EDGE

X = DISTANCE PUPIL LEADING EDGE HAS RECEDED FROM PLANE OF HMD PUPIL

FIGURE 10
RELATIONSHIPS FOR EYE PUPIL EDGE POSITION FOR EYE ROTATION OF W DEGREES

The results of repeated computations using equation 4 for each pupil condition, are plotted in Figure 11 out to 50 degrees off-axis, representing a hypothetical HMD design with a 100 degree horizontal monocular FOV. The inherent assumptions made here are that there is no field curvature for the HMD exit pupil at the design eye relief (accomplished either through highly corrected optics or optical/electrical compensation at the CRT), and that the eye is moving along its horizontal axis. One must also consider the movement of the edge of the eye pupil edge back from the plane of the HMD pupil as the eye rotates, because the HMD pupil becomes smaller at some rate dictated by the optical design, as one departs from the pupil location at the design eye relief point of the optics. This distance denoted as "x" in Figure 10 can be computed in a fashion similar to that for equation 4 using the relationship shown in equation 5.

$$\text{DISTANCE BEHIND PLANE OF HMD PUPIL} = x = r - h[\cot(v + w)] \qquad (5)$$

The results obtained applying this relationship are plotted in Figure 12, out to an eye rotation angle of 50 degrees, which again represents a binocular HMD system with a monocular FOV of 100 degrees. It remains for the optical designer to specify to the VPD system designer, how exit pupil size decreases as one moves away from its plane of maximum cross sectional area.

In addition to HMD FOV and eye movement considerations, the effects of exit pupil size on optical system weight must be considered. For wide FOV display systems, exit pupil sizes beyond about 10 millimeters cause the weight of the HMD optical elements to increase so substantially that they quickly become unacceptable for aircraft helmet systems. One can achieve a first cut approximation of exit pupil size and weight impact, on a particular optical system design, using the relationship defined by equation 6 and illustrated by Figure 13 [20]. To use the relationship expressed by equation 6, one must insure that the optical design is corrected for the Abbe sine condition [20], a relationship that expresses a condition that applies to optical systems free of certain aberrations for off-axis points, particularly primary coma [21,24]. Most high quality HMD designs are corrected for these aberrations.

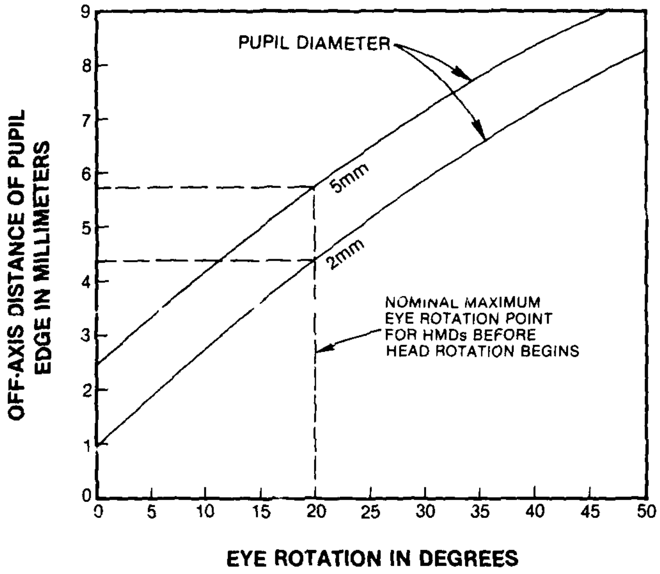


FIGURE 11
OFF-AXIS DISTANCE OF EYE PUPIL LEADING EDGE VERSUS EYE ROTATION ANGLE

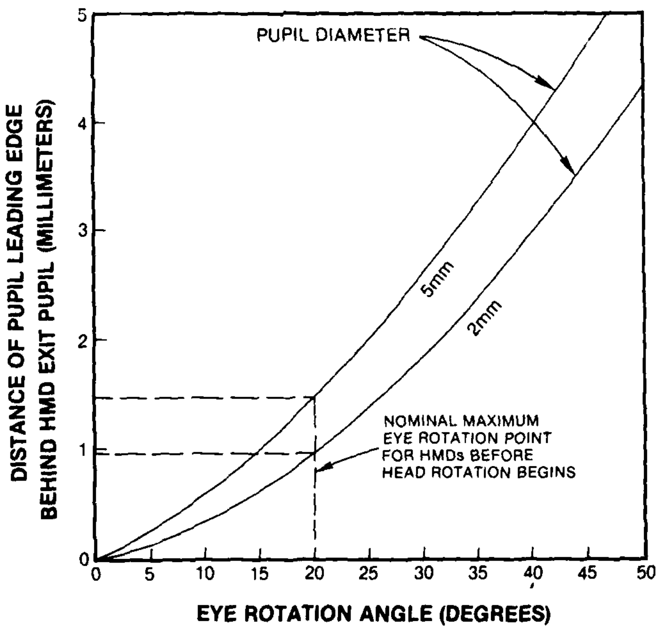
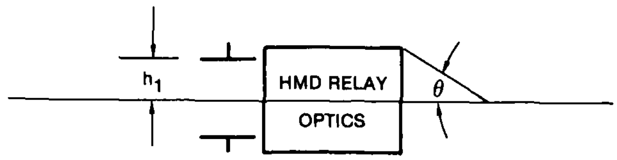


FIGURE 12
EYE PUPIL LEADING EDGE DISTANCE BEHIND HMD PLANE OF MAX PUPIL DIAMETER VERSUS
EYE ROTATION ANGLE



$$\theta = \mathrm{SIN}^{-1}(h_1/\mathrm{EFL}) \qquad (6)$$

WHERE: h_1 = HALF-HEIGHT OF EXIT PUPIL OF HMD OPTICS

θ = SEMI-CONVERGENCE ANGLE FOR HMD OPTICS INPUT FROM IMAGE SOURCE INPUT (CRT)

EFL = EFFECTIVE FOCAL LENGTH OF HMD OPTICAL SYSTEM

FIGURE 13
DEPICTION/EXPRESSION OF RELATIONSHIP FOR DETERMINING EXIT PUPIL SIZE

For an F-Theta mapped system, such as the Farrand Pancake Window HMD and, indeed, most binocular HMD designs, the effective focal length (EFL) for the whole system can be computed from equation 7.

$$\mathrm{EFL} = \frac{[\text{CRT FORMAT SIZE (HOR)}]}{[\text{HMD HOR FOV (DEG)}]} \times \frac{(180^\circ)}{\pi} \qquad (7)$$

Results, originally formally presented in reference [20], for both the growth in semi-convergence angle and relay optics weight, are again presented here, by Figures 14 and 15, for completeness and to stress the difficulty of obtaining large exit pupils, for the range of system focal lengths normally obtainable for HMDs (see Table 2).

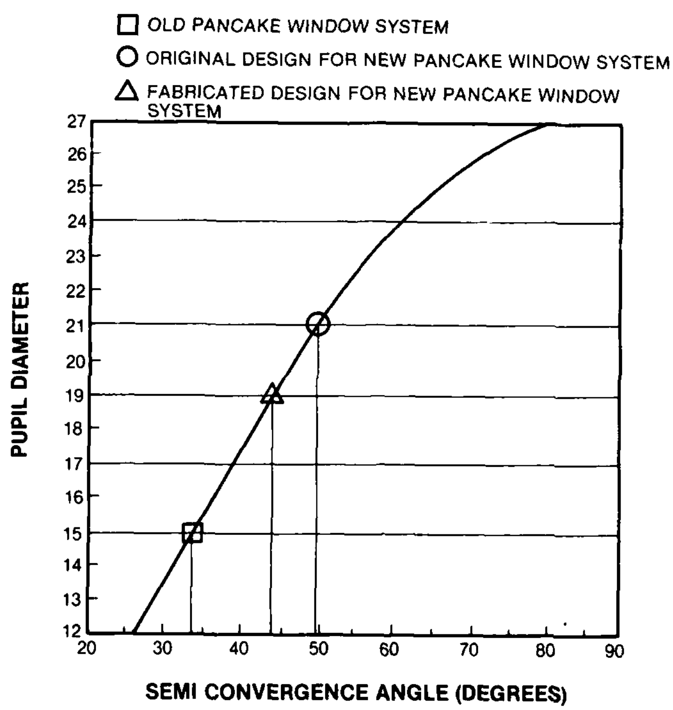


FIGURE 14
PLOT OF PUPIL DIAMETER VERSUS SEMI-CONVERGENCE ANGLE (PANCAKE WINDOW HMD)

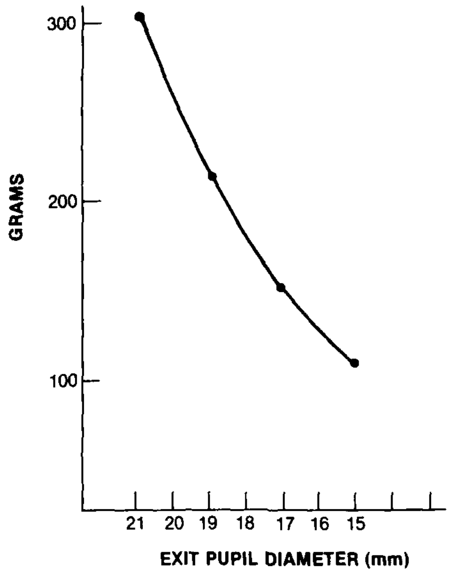


FIGURE 15
PLOT OF RELAY OPTICS WEIGHT VERSUS EXIT PUPIL DIAMETER (PANCAKE WINDOW HMD)

The remaining major factors affecting exit pupil size are the environmental operating conditions and the design of the headgear. Clearly, aircraft operating in a high "G" environment may need a larger exit pupil to prevent display vignetting due to helmet slippage on the head. This may be largely overcome by designing a system with a smaller more compact FOV with less eye relief, which in turn prevents the creation of significant inertial moments that would accentuate display movement from external forces. Also, as will be presented, the design of an integrated headgear which anticipates and attempts to prevent large helmet movements can also reduce the need for very large exit pupil sizes.

Hence, a generalized worst case condition might be hypothesized based upon, (1) feasible operational designs, which will probably not achieve a monocular FOV greater than 60 degrees horizontal by 45 degrees vertical (resulting in maximum off-axis angles of +/- 30 and 22.5 degrees respectively, and therefore, a radial angle of 37.5 degrees), and (2) the sparse human factors data related specifically to HMDs, which suggests that the human operator does not usually move his eye off-axis when viewing the HMD by more than +/- 20 degrees before moving his head. An important qualifier here, as mentioned in [20], are binocular display systems which rotate the HMD optical axis to achieve greater horizontal FOV, using partial overlap of the monoculars. Figure 16 depicts the exit pupil cross section, as it would appear located normal to the eye with no tilt of the binocular optical axes (which would be employed for a system having partial overlap of its monoculars). Also portrayed are important HMD system physical relationships. The relationships portrayed by Figure 16 should be considered a worst case condition, because the exit pupil size is based upon a full field condition. If the portion of the field (or object size), which must be visible simultaneously is reduced, then the diamond shape area, over which the reduced field can be simultaneously viewed, will become proportionally much larger. As Figure 16 shows, the only honest specification for eye relief/exit pupil size, is one that results in the proper positioning of the maximum cross-sectional pupil area on the eye. Other positioning points result in a reduced effective exit pupil size for no vignetting. If the orientation of the HMD exit pupil is normal to the cornea, then symmetric movement of the eye is possible with similar vignetting or lack thereof. However, if as noted in [20], the monocular HMD optical axes are turned out to obtain a partial overlap condition, then the movement to one side of the exit pupil (normally the direction for divergence of the eyes), is restrained for the nominal interpupillary distance (IPD) This must be compensated for by adjusting the optics to a somewhat wider-than-normal IPD (usually by 3-5 millimeters).

Given the preceding considerations, a worst case condition can be picked for the 5 millimeter pupil size at the 20 degree off-axis position, which results in a nominal indicated translation of + or - 6 millimeters. If one then adds to this + or - 3 millimeters of translation due to helmet movement (a reasonable amount for a well designed integrated helmet system, used for a rotary wing aircraft or simulator application), one arrives at a nominal exit pupil size of about 18 millimeters. In practice, at least for the breadboarded designs listed in Table 2, an exit pupil size of 14 - 17 millimeters has been found to be sufficient. For applications where weight is extremely important, a pupil size toward the low end of the range would probably be selected.

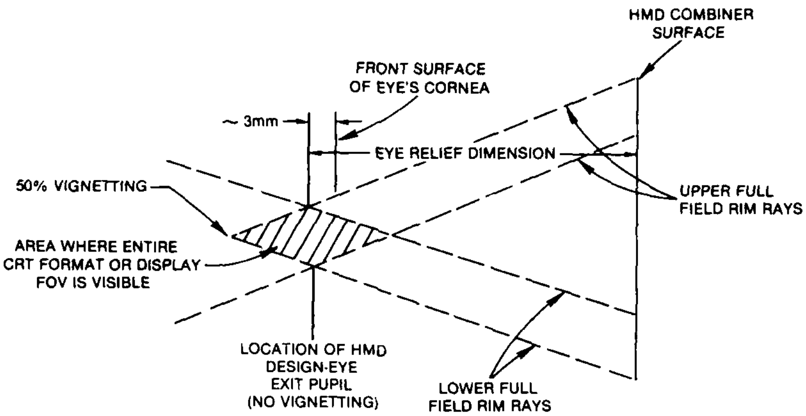


FIGURE 16
EXIT PUPIL/EYE RELATIONSHIPS

EYE RELIEF/CLEARANCE

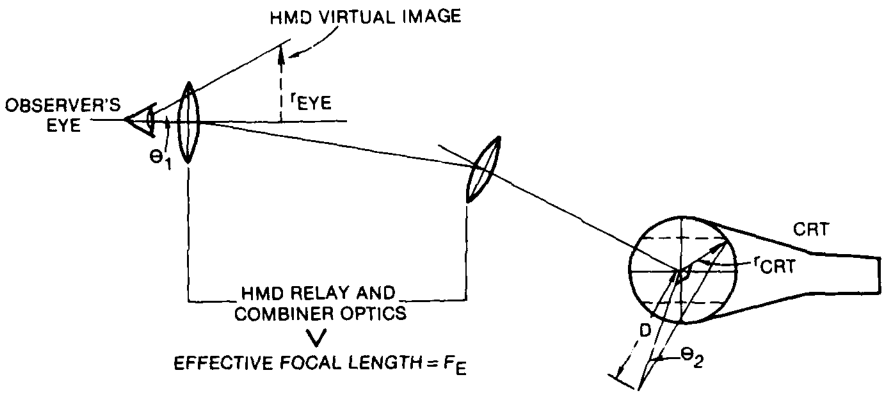
As depicted by Figure 16, the distance used to specify eye relief, should be measured from the viewing center of the final optical surface closest to the eye, to the optimal position for the largest cross-sectional area of the optics' exit pupil with respect to the eye. Table 2 lists a range of different distances for the five optical breadboards, which were developed as part of the VPD effort. Generally, designs providing 35 millimeters or more of eye relief, present no major operational problems, and allow most eyeglasses to be accommodated. However, it is prudent to keep eye relief as small as possible, because for a given FOV, as eye relief increases, so does the size and weight of the optics, in a manner proportional to the design approach employed. Another similar figure-of-merit (FOM), used to describe display system positioning around the eye, is eye clearance. The generally accepted meaning of this term is that it defines the point of closest approach of the HMD combiner and/or beamsplitter assembly to any part of the eye. A curved/tilted combiner assembly can often yield much smaller eye clearance distances than those given for eye relief. Experience with the breadboard designs listed in Table 2 shows that eye clearance distances of less than 20 millimeters present major difficulties, particularly when its use in an operational aircraft environment is contemplated.

COLLIMATION

For the VPD application, it is usually required that the display imagery, which is overlayed on the ambient or outside-of-cockpit-scene be at optical infinity (collimated). This permits minimal or no refocusing time between the HMD display and the outside world scene. It is also important because the helmet sighting system (as shown in Figure 1) uses the VPD HMD to image its sighting reticle. The reticle is electronically aligned with the helmet sensor during the system boresighting process. If the reticle image is not collimated, then there will be parallax error between the helmet sighting system and external scene for targets being designated by the display sighting reticle. Collimation can be checked by placing a powerful (20x magnification or higher) telescope focused for infinity in the HMD exit pupil, and checking for sharpness of the display imagery. If the imagery is in focus, one can usually be sure, that the display is collimated to within a small fraction of a diopter, which is normally sufficient. Display designs which have their combiner surfaces separate from the helmet lens or visor, usually maintain collimation much better than designs that use the helmet visor as the last display imaging surface. This is because visors are normally susceptible to deformations during helmet flexure, etc., which alter the focus of the display system. Attempts were made, early in the VPD HMD program, to develop an alternate focus or image location for the display format, so that the display imagery might also be optically located at the same distance as the cockpit instrumentation when the pilot was attempting to interact with internal cockpit instruments. The two conditions would be monitored by the helmet position/orientation sensing system and the image location would be rapidly shifted automatically. However, no compact, lightweight adjustment mechanism could be found and attempts to achieve this function were abandoned.

MAPPING/DISTORTION

For binocular HMD designs, particularly designs where the monocular fields are partially overlapped, F-theta mapping, which provides constant angular resolution over the display FOV, is often the best choice for the mapping of a display system's angular resolution [03,20]. However, F-tangent theta mapping, where the tangent of the field angle is proportional to the image source chordal height, represents the no-distortion mapping condition. F-theta mapping, where the image field angle is proportional to the image source chordal height, yields pincushion distortion. Therefore, some form of compensating distortion, nominally representing barrel distortion, must be introduced into the CRT imagery. The distorted CRT imagery corrects or linearizes the virtual image of the CRT when viewed through the HMD optics. Figure 17 depicts, in simple form, the mapping relationships between the eye and CRT, and shows the derivation of the relationship for the required correction. Alternate explanations of



F(Θ) MAPPED OPTICS $\Longrightarrow r_{EYE} = F_E(\Theta_1)$; WHERE Θ_1 HAS UNITS OF RADIANS

F – TAN (Θ) MAPPED CRT $\Longrightarrow r_{CRT} = D\,(\mathrm{TAN}\,(\Theta_2))$

IF NO DISTORTION PRESENT THEN $\Theta_1 = \Theta_2$

THEREFORE $r_{EYE} = F_E(\mathrm{ARCTAN}\,(\frac{r_{crt}}{D}))$

FIGURE 17
CRT/OPTICS MAPPING COMPENSATION

this problem may be found in [01,02,20,22]. The CRT drive electronics' deflection circuitry must be designed to support such correction. The VPD system integrator must be sure that the required correction, and, therefore, expansion or compression of CRT pixel spacing at different portions of the CRT faceplate, can be supported by the inherent performance of the CRT and its drive electronics. The arctangent function is difficult to implement with analog display electronics. Therefore, CRT deflection geometry correction is usually implemented by a truncated polynomial approximation, using terms out to third order, as discussed later in this paper.

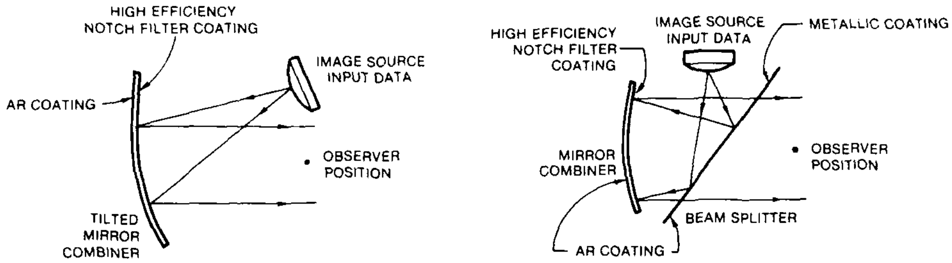
Residual field curvature may also be left in the optical design because its complete elimination would result in a larger number of optical elements and, correspondingly, a heavier design. This residual field curvature is usually reduced to negligible proportions by adding a corrective curvature to the CRT faceplate, resulting in some additional complexity for the CRT, but adding almost no additional helmet system weight. The shape of this curvature may be either convex or concave, depending upon the requirements of the optical design.

LIGHT MANAGEMENT (TRANSMISSION EFFICIENCY/MODULATION CONTRAST)

As mentioned much earlier in this paper, the contrast achieved for the displayed imagery and the amount of see-through permitted to the ambient scene is probably the most important design relationship for most HMD applications. This is especially true for the VPD, where the head mounted display is supposed to be the pilot's primary display device, and is critical for maintaining the required level of "situation awareness." For the systems listed in Table 2, the key to light management and the establishment of the proper transmission efficiencies for image source and ambient light is the design of the display combiner and/or beamsplitter elements.

The two most common configurations for the HMD combiner/beamsplitter (C/B) components, and their relationship with respect to the image source/relay lens input and observer's eye position, are shown in Figures 18a and 18b. The coatings used on each of the C/B surfaces are optimized for the intended range of applications including day/night viewing with symbology and/or imagery. They must also accommodate the performance of the image source, and its capabilities to adjust for the relative transmission efficiencies, for light arriving at the eye from the display image source or the outside scene. The most often used figure-of-merit (FOM) describing the quality of C/B light management (derived in reference [22]), is again listed here in equation 8 for completeness and the convenience of the reader who might want to compute hypothetical cases for the systems listed in Table 2. Equation 8 specifies the maximum amount of HMD contrast that can be achieved for a given viewing condition and the coatings design used in a particular HMD design. The value obtained in Equation 8, can be convoluted with (multiplied by) the system MTF computed for the CRT-drive electronics and optics, to obtain an estimate of total system MTF [22,23]. The derivation of system MTF relationships, for the CRT/optics combination, has been explained in reference 22, and will not be repeated here. Values for Cd of 0.2 to 0.3 are generally accepted as providing enough contrast to view line graphics symbology. Values for Cd of 0.8 to 0.9 are felt to provide enough contrast, to portray approximately 8 discernible linear $\sqrt{2}$ gray shades of imagery [22,23].

Insertion of a few values into equation 8, and a review of reference 22, should be sufficient to emphasize the importance of the type and quality of the C/B coatings. Systems utilizing a combiner system like that shown in 18a, such as systems 4 and 5 in Table 2, are, with current technology, much



VIRTUAL IMAGE DISPLAY USING A TILTED CONCAVE MIRROR

(a)

VIRTUAL IMAGE DISPLAY USING A SPHERICAL MIRROR BEAM SPLITTER

(b)

FIGURE 18
COMMON HMD COMBINER RELATIONSHIPS

$$Cd = \frac{(Li) \times (Rc)}{(Li) \times (Rc) + 2(Lb) \times (Tc)} \tag{8}$$

WHERE: Cd = CONTRAST (MAXIMUM) OF HMD IMAGE

Li = HMD IMAGE SOURCE LUMINANCE PRIOR TO COMBINER

Lb = BACKGROUND SCENE LUMINANCE

Rc = COMBINER REFLECTANCE COEFFICIENT (*) (FOR VPD HMD APPLICATIONS NORMALLY OPTIMIZED FOR P53 PHOSPHOR GREEN EMISSION PEAK)

Tc = COMBINER TRANSMITTANCE COEFFICIENT (*) (TOTAL SCOTOPIC TRANSMISSION)

(*) FOR WAVELENGTH SENSITIVE COATINGS, INTEGRATION OVER WAVELENGTH IS ASSUMED

more efficient light management systems, since they do not suffer the approximate 75% loss of luminance at the beamsplitter's metallic coating surface, as shown in 18b, and exemplified by systems 2 and 3 in Table 2. However, for the same FOV, systems like 4 and 5, which use primarily refractive optics to convey the CRT image to the eye, are usually much heavier than catadioptric designs, like systems 2 and 3. As described in [14], narrowband high efficiency multilayer dielectric coatings have been developed, which are tailored to reflect the primary spectral band of CRT phosphors, such as P43 and P53. These coatings allow most of the external ambient light to pass with minimal attenuation, except in the band set aside for reflection of the CRT image source light. A drawback to these coatings is that they require combiner designs where the incident angle of the image source light is almost constant across the entire FOV, and they attenuate a wider (60 to 80 nanometers) bandwidth than desired of the ambient visual spectrum [14]. A relatively new type of reflective/transmissive layer, dubbed a holographic simple mirror, has recently become available, and attempts are being made to incorporate this technology into HMD systems. Holographic simple mirrors are made from volume-phase reflection type holograms embracing photochemical, interference and refractive phenomena, and diffract light as conventional mirrors reflect light [09]. They seem to hold promise for moderating the angle-sensitivity and bandwidth problems associated with multi-layer dielectric coatings [09]. Multilayer dielectric coatings, with wide reflective bandwidths "notch out" a significant portion of the ambient spectrum, often adding a slight pink tinge to the ambient scene. In contrast, the holographic mirror technology offers the possibility of obtaining very narrow reflective bands of 10 to 20 nanometers or less, which can be tailored to the primary emission peak of the phosphor, thus allowing transmission of more of the outside ambient light. Antireflection (AR) coatings can be formulated from a number of materials [14, 15], and must be applied to prevent unwanted reflections that cause second surface ghosting, as explained in [22]. Problems with secondary image ghosts may be further reduced by striking an appropriate balance for the attenuation of ambient light, from the outside scene, using both surface coatings and continuous absorptive media throughout the combiner material.

An additional issue, not often discussed for HMD design and difficult to assess, is the optical system MTF and the relevancy of data supplied by the optics' manufacturers concerning MTF. A relationship, that can be used to compute a close approximation to tested optical system MTF performance, based upon preliminary optical design data, is given in equation 9. Using system 2, Table 2 as an example, the system f# would be 16.9/21, which equals 0.8. However, equation 9 must be modified to reflect the system MTF (that of the measurement system/HMD optics), or the "relative aperture" of the system. A reasonable setting for the measurement system is an aperture of 4mm, which reflects a midpoint for the

$$\begin{array}{c}\text{FOR}\\ \text{OPTICAL SYSTEM}\\ \text{DIFFRACTION}\\ \text{LIMITING RESOLUTION.}\end{array} \quad (\text{LINE PAIRS/mm}) = \frac{1}{(f\#)(\lambda)} \tag{9}$$

WHERE: $f\# = \dfrac{\text{EFFECTIVE FOCAL LENGTH OF OPTICAL DESIGN}}{\text{EXIT PUPIL (RELATIVE APERTURE) DIAMETER}}$

λ = WAVELENGTH OF LIGHT (IN MILLIMETERS)

eye's range of pupil sizes. The f# of the measurement system is then 16.9/4, which equals 4.225. Using the wavelength for peak green light for P53 phosphor of 545 nanometers (0.000545mm), equation 9 gives a diffraction limited resolution of 434 lp/mm. Using the normalized values for MTF, for an ideal aberration free system [21], as a function of percent of cutoff, given in Table 3, one may plot the the ideal theoretical MTF curves for the HMD/test instrumentation system, (assuming it is well corrected and free of significant aberrations), as shown in Figure 19.

TABLE 3
NORMALIZED MTF VALUES AS A FUNCTION OF PERCENT OF CUTOFF

PERCENT OF CUTOFF	MODULATION CONTRAST	PERCENT OF CUTOFF	MODULATION CONTRAST
0	100.0	55	33.7
5	93.0	60	28.5
10	87.3	65	23.5
15	81.0	70	18.8
20	74.7	75	14.4
25	68.5	80	10.4
30	62.4	85	6.8
35	56.4	90	3.7
40	50.4	95	1.3
45	44.7	100	0
50	39.1		

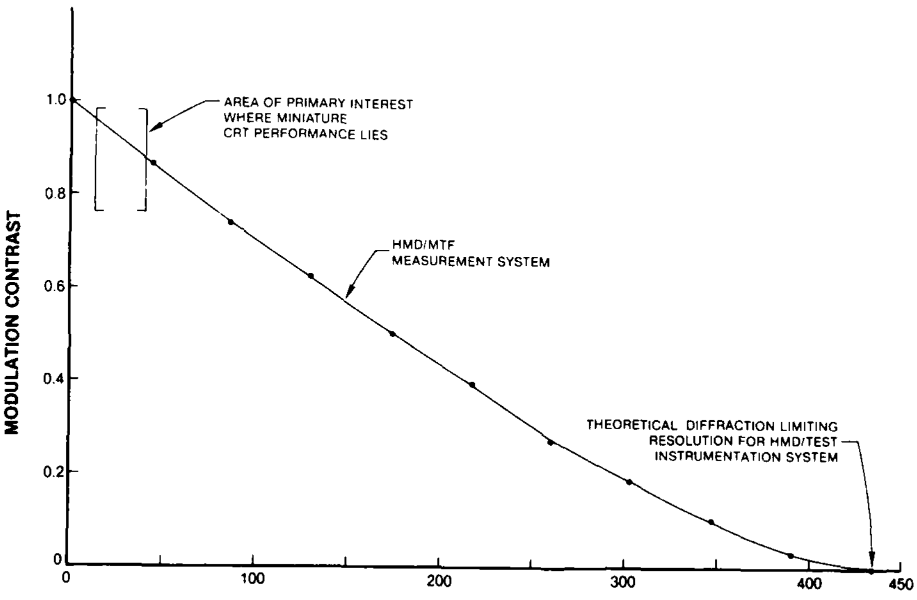


FIGURE 19
PLOT OF IDEALIZED OPTICAL MTF FOR MEASUREMENT SYSTEM/OPTICS

The bracketed area of Figure 19 highlights the region of interest, where the nominal performance of current CRT image sources fall. Current miniature CRTs resolve less than 40 lp/mm. Similar plots can be made for a particular HMD design, and used to check both the results of optics acceptance testing and combined with equation 8, to hypothesize more exactly expected HMD system performance. It must be stressed that the curve shown depicts highly ideal on-axis conditions. Measured values for the bracketed area of spatial frequencies, that depart markedly (i.e., down to about 50 percent response) from the representative curve shown in Figure 19, do not necessarily indicate an inferior optical design. However, the aircraft sensor system designer usually insists on reserving about 60 percent of the total sensor/HMD system MTF for the sensor system. The implication of this requirement for the optical design, is that values close to those shown in Figure 19 must be obtained, to allow total system MTF requirements to be met. In practice, it has been possible to achieve such values for certain HMD optical designs.

COLOR

The incorporation of a color-corrected design into the VPD HMD optics is certainly a desirable feature because color image source inputs can add significant additional information and cues. Color imagery may also aid "situation awareness," especially when the HMD sensor scene is the primary input from the outside world. More importantly, CRTs using narrowband phosphors, which may have significant spectral emission peaks at other wavelengths in the visual spectrum, need not be filtered, and therefore, all of their light can be used to maximize luminance contrast at the display combiner. However, color-corrected optics usually result in a system with many more optical elements, increasing helmet weight significantly. As Table 2, shows, only one of the five VPD HMD breadboards is a polychromatic design because of the extreme weight penalties, that are associated with full color-corrected designs. An even more important factor is that the combiner, must now incorporate lower efficiency broad spectrum reflective coatings for the HMD image source light, and, consequently, the advantage of using a narrow band reflective/broadband transmissive coating scheme, to maximize transmission of both the image source and ambient light, is lost. Luminance contrast ratios between the HMD imagery and the ambient scene may also be reduced.

Monochromatic HMD designs require narrowband phosphors to avoid lateral and axial color. Lateral color artifacts produce a blurred second image of a different color, due to differences in image magnification. The result is different image sizes for different wavelengths of light [21]. Axial color artifacts show up as longitudinal chromatic aberrations, due to light rays of differing spectral wavelength, undergoing different amounts of refraction [21]. These color aberrations are often most noticeable at the edge of the HMD exit pupil. Tolerances for axial and lateral color that seem to have worked well for the VPD systems are provided in the section concerning miscellaneous optical specifications in Table 4.

The phosphor of choice for the VPD HMD designs has been P53, because of its extremely rugged thermal and emission life characteristics and luminous efficiency. The yellow-green primary emission spectrum of P53 provides good color contrast against colors found in land/sea terrain, and is close to wavelengths, where the eye's spectral response is at a maximum. P53 though, has significant red and blue emission peaks which must be removed for proper operation with the VPD HMD monochromatic designs. For systems that require glass CRT faceplates, attempts were made to utilize multilayer coatings developed by Optical Coating Labs Inc. (OCLI) between the CRT phosphor and faceplate that would both filter out the red or blue peaks, and allow more of the green light to exit the faceplate [15]. These antihalation coatings, when used with a compatible antireflection coating on the outside surface of the faceplate, also enhance the display contrast obtained from glass faceplates CRTs. Preliminary experience with these coatings shows that improved contrast and luminance are obtained, but some residual and noticeable red and blue light is still transmitted. This has required the inclusion of a green transmissive filter, to completely suppress remaining red or blue emissions. For VPD HMD monochromatic designs which require a shaped fiber optic faceplate, the green transmissive filter is also needed. Use of the OCLI coatings with fiber optic faceplate systems has not been possible to date, because their physical properties do not provide necessary tolerance to the high temperatures to which the coatings/faceplate are subjected during the coating deposition process.

MISCELLANEOUS VPD OPTICAL SYSTEM SPECIFICATIONS

Remaining miscellaneous VPD HMD system parameters and suggested tolerances that have produced satisfactory results for the breadboard systems listed in Table 2 are listed in Table 4. Some additional explanation should be given here concerning the requirement for IPD adjustment and alignment (allowed divergence, dipvergence, etc.). The calculations for maximum exit pupil size, covered earlier, do not include provision for centering the HMD exit pupils for an individual's eye center-to-center distances. Interpupillary distances vary from between 55 to 74 millimeters for the 1st to 99th percentile for adult humans, so some reasonable allowance must be made for this variation to prevent vignetting, while minimizing the range of adjustment allowance, which can have a significant impact on the helmet/display optics interface and system weight. The variation given in Table 4, specifies a range that appears to have produced satisfactory results, but should not be considered definitive.

Alignment tolerances are also felt to be critical, because, while human accommodative (focus) and convergence powers are substantial, failure to insure proper alignment, may result in fatigue and psychovisual problems of unsuspected origin during extended operational use of a misaligned system. Divergence, which is an unnatural and difficult condition for the eyes, should be set to zero. This is normally easily accomplished, because the binocular HMD is adjusted to error toward some convergence, during mechanical/electronic alignment. However, convergence can produce false stereoscopic cues between the monoculars and, therefore, should also be minimized. A reasonable convergence setting should produce an accommodation error of less than a tenth diopter. This setting can be computed using the relationship, that convergence distance in millimeters, equals the interpupillary distance (IPD) in millimeters divided by the convergence error in radians. For a nominal IPD of 63 millimeters, and 12 arc minutes of convergence, as given in Table 4, the convergence distance is 10,938 millimeters or 10.9 meters. Since diopters equal the reciprocal of distance in meters, the convergence error represents

less than a tenth diopter, which is an appreciably smaller error than that in prescription spectacles. It remains for operational testing of the VPD binocular HMD to verify that this criteria provides satisfactory results, or should be modified. Dipvergence should also be made as close to zero as possible to prevent mismatch between symbology or scan lines. Normally, a dimensional tolerance of one scan line width (about 3 arc minutes) is desired, but cannot be provided by the optics/headgear adjustments alone, so proper electronic alignment patterns and adjustment capability, must be incorporated into the CRT display electronics.

TABLE 4
SUMMARY OF MISCELLANEOUS REQUIREMENTS FOR VPD HMD OPTICS

ABERRATIONAL DISTORTION	
CENTER	UP TO 0.2 PERCENT
MAX OFF-AXIS	UP TO 0.5 PERCENT
COLOR (MONOCHROMATIC APPROXIMATION)	535-555 NANOMETERS
AXIAL COLOR	LESS THAN 1.5 ARC MINUTES
LATERAL COLOR	LESS THAN 3.0 ARC MINUTES
MAGNIFICATION IMBALANCE FOR BINOCULAR DISPLAY CONFIGURATIONS	LESS THAN 1 PERCENT
SEE-THRU DISTORTION	LESS THAN 2 PERCENT
MAXIMUM CONVERGENCE/DIVERGENCE	12/0 MINUTES OF ARC
MAXIMUM DIPVERGENCE	6 MINUTES OF ARC
PERIPHERAL VISION OCCLUSION	MINIMIZED
IMAGE-TO-GHOST RATIO	120/1
MAXIMUM ACCEPTABLE LIGHT IMBALANCE	0.5 PERCENT (OPTICS ONLY)
BINOCULAR IPD ADJUSTMENT	58 TO 72 MILLIMETERS

VPD HMD IMAGE SOURCE

As explained earlier during the discussion concerning VPD design alternatives (see Figure 3), the HMD with head mounted image source was selected as the only viable alternative, given the current state of technology. Great strides are being made with solid state image sources, and laser generated displays loom on the horizon as a potentially powerful alternative. Even so, significant advancements have also been made in miniature CRT technology, which still makes them the current best choice for a VPD HMD application. Besides their basic light conversion efficiency and resolution, there are other reasons for selecting the CRT. One is that CRT image source technology does not impose a strict allocation of display elements across the display format whose relative size and activation characteristics are fixed. Therefore, horizontal/vertical smoothing (antialiasing) techniques, may be applied to smooth the appearance of straight edges (particularly from man-made objects), that cross the scanning format diagonally, producing staircasing effects and visual artifacts. Generally, a solid state display requires several times the inherent resolution of a CRT to match the apparent smoothness of the CRT's imagery. Since current miniature CRTs can provide in excess of 1 million resolution elements, solid state displays for HMDs have significant performance barriers to overcome. In small sizes they currently have much lower resolution than CRTs. In addition, a CRT image source may present randomly-written vector graphic information, providing only smooth line segments at any orientation on the display. This symbology may be updated at refresh rates much higher than normal video field rates to achieve much brighter peak line luminance levels for daylight viewing. This is possible by taking advantage of optimum charge pumping techniques, which some of the new rare earth phosphors permit [04]. For these reasons, only the CRT image source is considered.

Figure 20 depicts the direct impact on miniature CRTs of certain image source parameters due to the requirements for good display contrast and resolution on the HMD, especially when employing a see-through combiner. CRT Line widths must be kept small, and active area format sizes made as large as possible, given an overall maximum allowed CRT diameter of about one inch. Line rates, refresh rates and, as possible, anode potentials must be increased to balance resolution and light conversion efficiencies. At the same time, faceplate contrast must be preserved so that individual adjacent resolution elements remain distinct and discernible to the eye. This requires a high efficiency, fine grain size phosphor formulated for optimum light emission/transparency and thermal conductivity, coupled with a faceplate system, such as those using fiber optics, which offer improved contrast.

To bring about substantial performance gains in the CRT during the VPD HMD effort, an attempt was made through a number of studies [04,17,18], to identify major problem areas, where improvement had to be made. These are listed in Table 5. Improvements in the problem areas listed in Table 5, had to be made in the context of the design limitations imposed, by the electromagnetic deflection(EMD)/ electrostatic focus lens (ESFL) system, which has been found to be most suitable for miniature CRT applications. A representative CRT design, showing the major relationships between internal

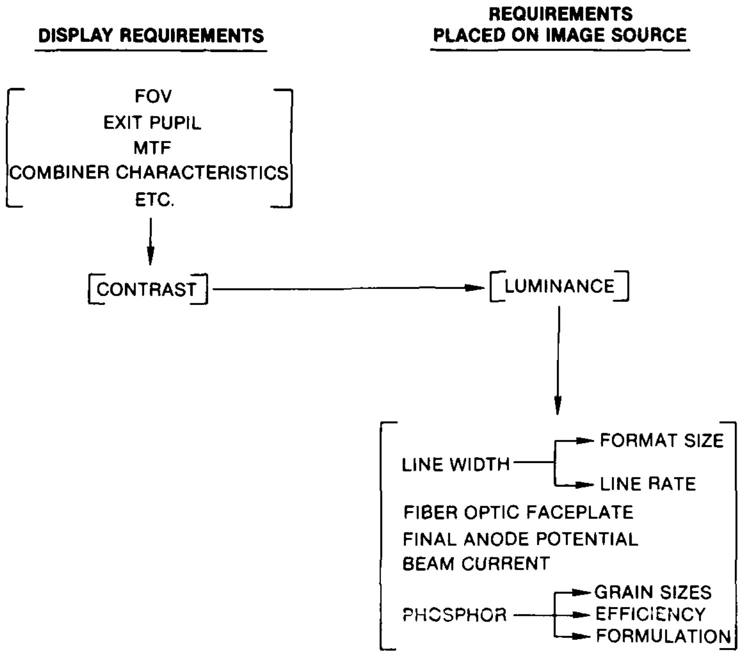


FIGURE 20
DISPLAY REQUIREMENT IMPACT ON IMAGE SOURCE PERFORMANCE

TABLE 5
MAJOR PERFORMANCE LIMITING PROBLEM AREAS FOR MINIATURE CRTS

CRT FACEPLATE SYSTEM	ELECTRON OPTICS	OTHER PROBLEMS
MAINTAIN HIGH LUMINOUS EFFICIENCY DURING ALL CRT DRIVE CONDITIONS	ELECTRON OPTICS CAPABLE OF FOCUSING SMALL BEAM DIAMETER AT HIGH BEAM CURRENTS	ACCELERATION VOLTAGE
		CRT's PHYSICAL SIZE
	THERMAL LIMITATIONS	MAGNIFICATION
MINIMIZE PHOSPHOR'S CONTRIBUTION TO BEAM SPREADING/LINE WIDTH		GETTERING
	SPACE CHARGE SPREADING	DEFLECTION YOKE PERFORMANCE
IMPROVE CONTRAST	ABERRATIONS	CATHODE LOADING

components, is diagrammed in Figure 21. Although new and promising alternatives are being investigated [18], nearly all ESFL designs for CRTs use either; (1) bipotential lenses or, (2) unipotential or einzel lenses. In general, better center resolution is achievable with bipotential lens CRTs than unipotential lens CRTs, because of the more favorable beam diameter magnification value associated with bipotential lens designs [17,18]. A first cut at determining the magnification and, therefore, beam spot size (ignoring the effects of the phosphor faceplate system) may be made as shown in equations 10 through 12.

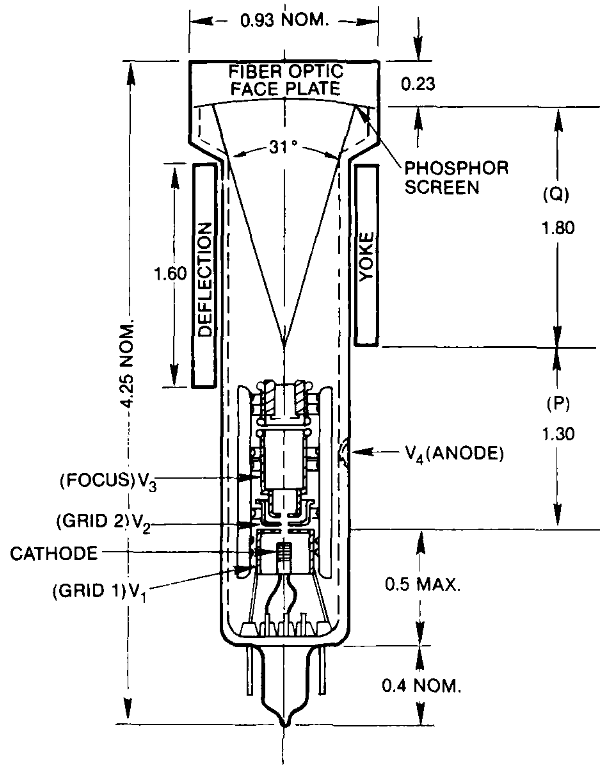


FIGURE 21
REPRESENTATIVE EMD/ESFL BIPOTENTIAL LENS MINIATURE CRT

$$\text{GEOMETRIC MAGNIFICATION} = M_1 = Q/P \tag{10}$$

WHERE: Q = DISTANCE FROM DEFLECTION CENTER TO SCREEN

P = DISTANCE FROM G_1/G_2 CROSSOVER TO DEFLECTION CENTER

$$\text{ELECTRONIC MAGNIFICATION} = M_2 = (V_3/V_4) \tag{11}$$

WHERE: V_3 = CRT FOCUS VOLTAGE

V_4 = CRT FINAL ANODE VOLTAGE

$$\text{OVERALL MAGNIFICATION} = M_3 = M_1 \times M_2 \tag{12}$$

For the CRT shown in Figure 21, which might operate at an acceleration potential of 13 kilovolts, and nominal focus potential of 2.5 kilovolts, a value for M_3 of 0.266 is obtained. This value may be multiplied by the virtual crossover diameter, supplied by the CRT manufacturer, to determine a first order approximation to spot size, ignoring phosphor/faceplate system contributions. Unipotential lenses give better center-to-edge uniformity than bipotential lenses [17,18]. This advantage can be overcome by using shaped fiber optic faceplates, which minimize deflection defocusing and using dynamic focus voltage correction, which minimizes focus lens aberrations while maintaining the significant spot minification advantage demonstrated by equation 11. Therefore, for the VPD HMD effort, bipotential lens designs were given primary emphasis.

An accepted method of determining a FOM for CRT performance, which is in essence one for spot size or resolution, for a given luminance level, is to determine the RSS (square root of the sum of the squares) of the individual contributing factors to CRT spot size. Such a relationship, presented in slightly different form in many references [12,17,18], and taken from [18], is given in equation 13. For the VPD effort, the major design emphasis focused on maximizing the CRT's final anode potential, while remaining within safe operating limits, investigating the effects of increasing the G_2 voltage and raising G_1 cutoff, maximizing the effective cross-sectional area of the focus lens, improving deflection yoke characteristics, and optimizing phosphor grain size/composition/deposition techniques.

$$d^2_{TOT} = d^2_{1st\ ORD} + d^2_{SPHER} + d^2_{ASTIG} + d^2_{SP\ CHG} + d^2_{PHOS\ SCR} \qquad (13)$$

WHERE: d_{TOT} = TOTAL SPOT DIAMETER MEASURED AT CRT VIEWING SURFACE

$d_{1st\ ORD}$ = DIAMETER OF FIRST ORDER CONTRIBUTION (MAGNIFICATION OF GRID 1/GRID 2 CROSSOVER)

d_{SPHER} = DIAMETER OF SPHERICAL ABERRATION CONTRIBUTION

d_{ASTIG} = DIAMETER OF ASTIGMATISM CONTRIBUTION

$d_{SP\ CHG}$ = DIAMETER OF SPACE CHARGE CONTRIBUTION

$d_{PHOS\ SCR}$ = DIAMETER OF PHOSPOR SCREEN CONTRIBUTION

Raising the final anode potential effectively provided more luminance for the same beam current. Utilization of a lower current, and a higher voltage operating mode meant that, for particulate phosphor screens, longer phosphor life was achieved. Also, at 12 kilovolts or more, space charge spreading effects became negligible with the beam currents and beam travel distances found in miniature CRTs. However, the higher anode potentials meant a stiffer beam for the magnetic deflection yokes to steer. Therefore, new, higher current, low inductance/low capacitance deflection yokes were designed [10]. These new yokes also run cooler at higher deflection coil currents. The deflection yokes are driven by appropriate highly linear deflection electronics circuitry that can support the high video line rates, often needed for VPD applications.

Maximum focus lens diameters and gun limiting apertures have been successfully implemented in an integrated CRT design [17,18]. These improvements coupled with shaped faceplates, the implementation of dynamic focus correction into the CRT drive electronics, and lengthening the CRT slightly so that the deflection yoke assembly does not overlap the focus lens element [10], have effectively reduced aberrational/astimatism contributions to about 10-15 percent of the total spot size. This may represent a practical limit to a reduction of these contributions to spot size, and left only first order contributions and phosphor screen effects, where further reductions might be obtained.

The major factors that contribute to first order spot size are interrelated and expressed by Langmuir's equation (equation A3.19, reference [12]), as given here by equation 14. Its form is derived for narrow-angle beam assumptions; i.e., higher order contributions to spot size are negligible, because the radial displacement and angle of the beam are kept small [18]. Equation 14 then represents an upper limit for display performance (ignoring phosphor screen contributions), and, once a CRT has been optimized for a given set of operating characteristics, indicates the only possible ways, that higher current densities (more luminance for a given spot size) can be achieved. A closer look at equation 14 shows that there are essentially four parameters which may be varied to increase

$$P_s = P_c\,[(eV/kT) + 1]\,\sin^2\theta \qquad (14)$$

WHERE: P_s = PEAK CURRENT DENSITY AT SCREEN

P_c = PEAK CURRENT DENSITY AT CATHODE

V = FINAL ACCELERATING POTENTIAL

T = CATHODE TEMPERATURE

e = ELECTRONIC CHARGE

k = BOLTZMANN'S CONSTANT

θ = MAXIMUM HALF-ANGLE OF CONVERGENCE AT CRT SCREEN

peak current density at the phosphor screen; (1) increase the acceleration potential, (2) increase the angle of convergence at the screen, (3) reduce the operating temperature of the cathode, and (4) increase the peak emission current capability of the cathode. The acceleration potential has already been raised, and 13 kilovolts appears to be a maximum reliable operating potential. Modifications to the triode and focus lens design within the allowed dimensional limits of miniature CRTs, have also brought the angle of convergence to near its absolute maximum. Therefore, the designer is left with the option of reducing the object beam diameter. A practical way to accomplish this reduction is to reduce the G_1 aperture (see Figure 21), which increases the peak cathode loading. Projections for peak cathode loading in advanced CRT designs currently predict peak emission densities of 5 to 10 amps/cm^2, which is well above, that which can be obtained for standard oxide cathodes, providing reasonable life characteristics [18]. The search for cathode designs, that can meet these operating requirements is perhaps the chief remaining breakthrough to be achieved for miniature CRTs with the performance needed to accommodate most VPD applications.

The remaining area left for obtaining performance improvements is the phosphor screen characteristics. A significant impediment to past performance improvements in this area, had been knowing what the actual beam diameter was, just prior to beam impact on the phosphor. This dimension could then be compared to the spot size of light, emanating from the phosphor, after impact of the beam. At the start of the VPD effort, AAMRL had a significant parallel effort with AT&T, Bell Laboratories to develop improved versions of single crystal phosphors (SCP) that had superior thermal characteristics and did not suffer coulombic degradation which causes diminished light output for the same power input. Their cathodolumiescent qualities, also produced a spot of light that was almost the same diameter as the electron beam spot, impinging on the rear surface of the phosphor [04]. While these materials exhibit superior contrast at all drive levels, they have not produced the external luminous efficiencies originally hoped for. However, they have proven to be very significant design tools, and have provided important technical insight into the improvement of particulate phosphor CRT screens. Fabricated in split-screen versions, where one-half of the CRT screen has an activated SCP, and the other half a given formulation of a particulate phosphor the CRT designer could then know the contribution to spot size made by the particulate phosphor by measuring the change in spot size as the electron beam scanned across the two media. This has allowed the importance of a number of particulate phosphor parameters to be investigated, including; (1) the optimization of phosphor thickness, and therefore, its transparency to light generated by the e-beam for a given acceleration potential, (2) the optimization of grain size mixtures, to achieve high resolution, high luminous efficiency, good thermal conductivity and good operating life characteristics, and (3) the evaluation of phosphor deposition processes that yield good percent coverage of the screen, and optimized phosphor grain packing. These processes, although much refined, are still undergoing further improvement.

Figure 22 depicts the performance gains achieved for an improved miniature CRT developed as part of a joint AAMRL/Hughes Aircraft Company development program. For the reference CRT, shown in Figure 22, measured at 50 percent peak luminance line widths of 0.75 mils (19 microns) and 1.0 mils (25.4 microns), luminances of 1100 and 1300 ft.-Lamberts were obtained. For the improved CRT measured at the same line width conditions, peak line luminances of approximately 4300 and 7350 ft.-Lamberts respectively, were achieved.

The peak line luminance FOM is useful for indicating improvements made for operating conditions that might be expected of an HMD for the presentation of symbology under daylight viewing conditions. CRTs of this type are also expected to provide similar improvements for raster imagery presentations. However, comprehensive CRT measurement at different spatial frequencies and luminance conditions, made with CRT drive electronics which are capable of preserving the inherent performance of these new CRTs, were not available in time to include here.

Operating a miniature CRT at the high luminance, high current levels indicated in Figure 22 does exact a toll, primarily a shortened operating life. The current family of improved CRTs is expected to provide only 70 to 80 percent of its peak performance after 400 hours of operation. The prime culprit appears to be the emission characteristics/life of the cathode, and not coulombic degradation of the phosphor. Improved cathode materials and designs, such as new low noise variants of dispenser cathodes, which operate at power levels that do not produce severe grid emission, are being sought, but no clear replacement for refined high grade oxide cathodes has been firmly established. At the same time, further iterations in electron gun design and phosphor screen compositions are expected to produce further improvements of at least 20 percent above the CRT performance depicted in Figure 22 by the first half of 1988.

INTEGRATED HELMET SYSTEM (IHS)

GENERAL CONSIDERATIONS

During the VPD HMD development it was determined that a successful VPD design effort would require the design of a helmet which optimized the integration of the optics and image source components about the head. Other requirements, such as the need to demonstrate a helmet system that protected the human in hostile chemical and biological environments, also had an impact on the types of helmet systems that were evolved. Indeed, probably almost all HMD applications, including narrow FOV HMDs, would benefit substantially from a custom integrated helmet system design. A perfect example is the Kaiser, Inc. "Agile Eye" helmet system which incorporates a helmet position/orientation system and a HMD, which can, for two different design variants, provide a monocular visor projected display, with an instantaneous circular FOV of either 12 or 20 degrees. Because of the small FOV, this system was able to improve upon helmet weight and CG characteristics currently found in unmodified operational flight helmets intended for use in fighter aircraft.

For the VPD effort, the integrated helmet design attempted to provide the necessary operational safety while minimizing weight and optimizing CG, enhance the operation of VPD components, minimize the impact of environmental factors on the visual/auditory functions, and as possible, provide the

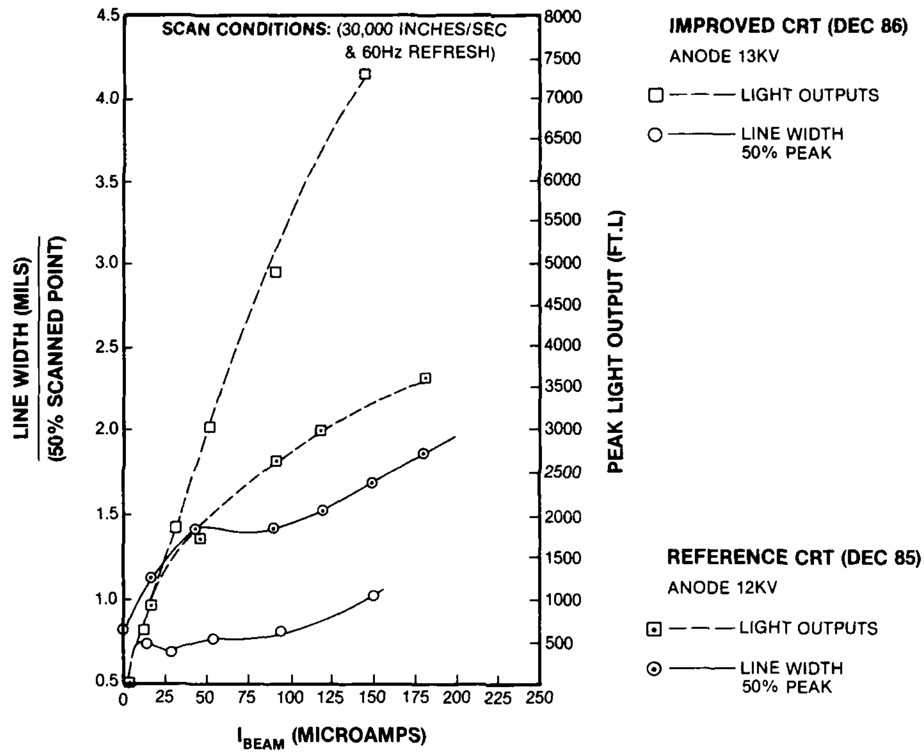


FIGURE 22
COMPARISON OF MINIATURE CRT PERFORMANCE IMPROVEMENTS

necessary comfort for extended periods of wear. Design features and considerations that proved to be most important to the successful intégration of each optical system design were as follows:

1) The selecti n and performance of the HMD optics design

2) The helmet/optics head stabilization methodology

3) Helmet/optics interface issues affecting adjustment capability for the optics

4) Basic helmet design alternatives

SELECTION OF HMD OPTICS DESIGN/PERFORMANCE

The selection of a particular optical design configuration is just as important as its required performance in its effects on the effectiveness of the final system hardware. The selections made often affect head/helmet CG more than weight. Figure 23 illustrates the most feasible HMD optical system configurations. The location of the optical system's head-mounted image sources imply a particular relay optics design to bring the image to the human's eyes. Location 1, which indicates a mounting location anywhere across the top or crown of the helmet, permits a reasonably simple and short relay optics, but results in a significant modification of the head/helmet CG and a "topheavy" feeling. Locations 2 and 3 still normally utilize relay optics of modest complexity, but are located lower on the head, and have a lesser, but still significant (especially location 3) effect, on head/helmet CG. A problem with location 2, is that it normally occludes peripheral vision, and therefore, necessary peripheral motion cues that are important to military pilots during the performance of low level and hovering flying tasks. One noteworthy advantage of location 3 is that it provides the optimal path for achieving large HMD vertical FOVs. However, it also presents a more difficult problem for eliminating stray images emanating directly from the relay optics to the eyes. Location 4 provides an optimal location for achieving "operationally positive" modifications to the head helmet CG, but results in excessive helmet weight for a given FOV. This happens because, in supporting the high resolution/large FOV operating conditions, either heavy refractive optics or fiber optic image conduits, must be used to relay the CRT images to the eyes. Location 5 presents a compromise that permits shorter fiber optics conduits or reasonably-sized high efficiency refractive relay optics to be used, while still resulting in a head/helmet CG modification that is altered in a desirable direction. Normally, location 5 employs a refractive relay optics design, that carries the CRT image up and over the ear, to the

display combiner without significantly occluding peripheral vision. The VPD helmet systems described in this paper have made use of only mounting locations 1, 3, and 5.

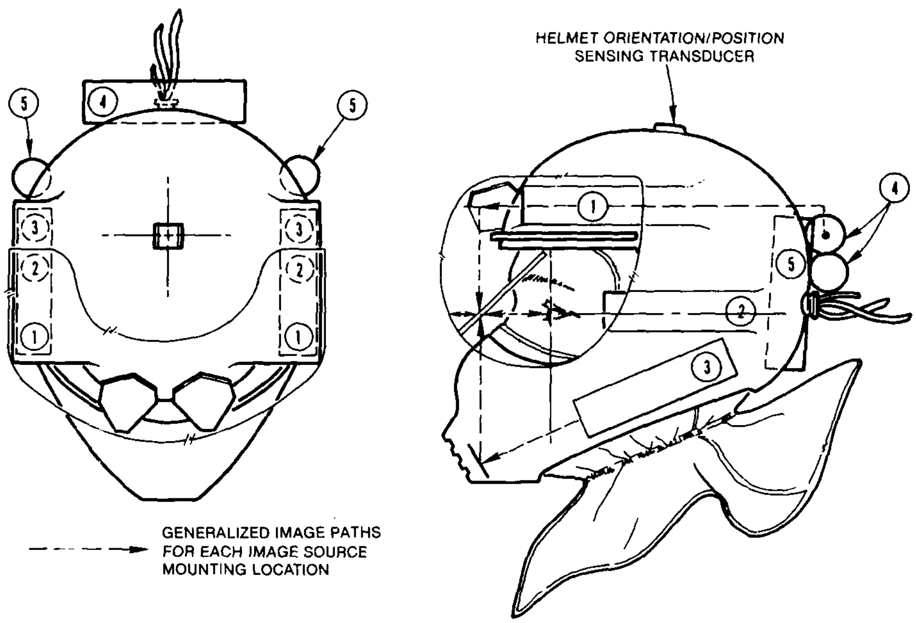


FIGURE 23
IHS MOUNTING LOCATIONS FOR VPD HMD COMPONENTS

The alteration of head/helmet CG is a critical parameter affecting the selection of the HMD optical design. The VPD program is now in the breadboard stage, where designs and materials are fluctuating, and it has not been possible to predict head/helmet CG modifications, based upon dimensional predictions of helmet relationships and the densities of the materials used. Instead, the breadboards are being completed, and then the Mass Properties Instrument built by Space Electronics, Inc. and located at AAMRL, is being used to measure the center of mass/gravity and determine mass moments and products of inertia. These measurements will then be used to predict CG based upon desired modifications to a given design, as improved systems are fabricated for operational testing.

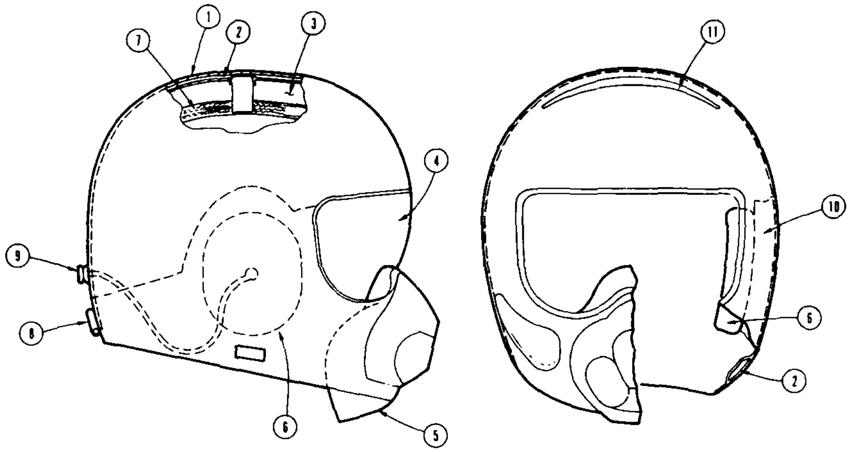
One additional important consideration that can have a direct impact on integrated system design is the susceptibility of the optical design to stray light. Stray light paths can produce unwanted reflections of ambient structures within the HMD FOV that compete in a very objectionable manner with the display imagery. The two major factors affecting this problem are the selection of the image path for a particular optical design, and the eye relief provided for the display's combiner. Greater eye relief leads to more severe problems. Light originating from behind helmet, or overhead often presents the most severe problem. These problems, cannot be fully corrected through the use of antireflective coatings, and usually require the addition of opaque sections around the optics or the extension, and/or thickening of the helmet shell/liner combination, to block objectionable stray light paths.

HELMET STABILIZATION

The inclusion of relatively large exit pupils and IPD adjustment in the optics/helmet design is not enough to insure, during normal viewing/operating conditions, that the helmet system will not move sufficiently, thus vignetting a portion of the display's instantaneous FOV. Therefore, some sort of stabilization scheme must be incorporated. While there are several options, the approach chosen for the VPD HMD effort was one which incorporated an oxygen mask that could be rigidly held with respect to the rear portions of the helmet, as suggested by the helmet concept illustrated in Figure 23. This arrangement allows a rigid lever arm to be formed, between the nape of the neck and the bridge of the nose, that resists both vertical and sideways movement of the helmet. This scheme has proved to be very successful, and eliminates most helmet position hysteresis following rapid head-slaving movements. Comfort/facial access must also be considered, and most designs allow a mask design that can be opened to one side, although a design employing mounting location 3 sometimes effectively eliminates this option. An additional benefit of this type of helmet design is that the optical design and associated adjustment requirements may, through the rigid mask design, be referenced to the bridge of the nose. This scheme offers one of the most stable, reliable reference methods for the eyes, given human anatomical characteristics.

HELMET/OPTICS INTERFACE ISSUES

• Three types of adjustments must be provided to properly position the optics with respect to the eyes: horizontal (IPD), vertical, and depth (eye relief) adjustments. IPD requirements have already been discussed in sufficient detail, except to stress that the helmet system must permit separate independent adjustment of each monocular, and the adjustment must be parallel and colinear to insure that misalignment of the binocular scene does not occur for different adjustment points, anywhere in the allowed range of movement. Vertical and depth adjustments imply a personalized custom mounting scheme. For the VPD designs, this has been accomplished through the use of a custom "thermal plastic liner (TPL)," developed by Gentex, Inc., and inflatable air bladders whose internal pressure may be controlled through the use of a miniature helmet-mounted finger pump and valve assembly, operated while viewing alignment patterns on the display optics. Investigations aimed at determining whether this mounting/adjustment technique provides the desired amount of stability and comfort are ongoing. Major features of the VPD IHS are depicted in Figure 24.



FEATURES:

1. LIGHT WEIGHT KELVAR SHELL
2. PLENUM (PART OF LAYERED SHELL, AIR DUCT FOR VENTILATION)
3. STYROFOAM LINER
4. PROTECTIVE POLYCARBONATE VISOR
5. OXYGEN MASK ASSEMBLY
6. HEADPHONE EAR CUP ASSEMBLY
7. TPL CUSTOM FITTED LINER
8. AIR HOSE CONNECTOR
9. FINGER AIR PUMP FOR EARPHONE/ DISPLAY ADJUSTMENT BLADDERS
10. EARPHONE ADJUSTMENT BLADDER
11. VERTICAL ADJUSTMENT BLADDER

FIGURE 24
IHS HELMET SYSTEM CHARACTERISTICS

HELMET DESIGN ALTERNATIVES

The integration of the VPD optical prototypes into representative military headgear systems, using advanced lightweight Kevlar shells, has resulted in a number of interesting helmet configurations. These designs were driven by a number of considerations, including the desire to achieve the largest FOV/exit pupil for a given HMD design approach, expected operational conditions in flight test aircraft, abuse that normal personal equipment undergoes, difficulties with doning complex helmet systems of this type, safety, particularly for rapid egress from a damaged air vehicle, and the physical properties of the designs as discussed for CG, etc. Several of the more interesting IHS breadboards are presented here in Figures 25, 26, and 27 for systems 3, 2, and 5 respectively, from Table 2.

The Dual Mirror system, Figure 25, provides the second largest FOV of any of the designs and achieves the lowest optical system weight. Its design is closely integrated with the oxygen mask, which aids in referencing the optical alignment to the eyes, but complicates the ability to remove the mask when the helmet is worn. The close integration with the mask, led to a rear entry design, which eliminates cumbersome, overhead doning of the helmet and streamlines the placement of the oxygen mask and optics over the face. The folds and contours of the helmet shell at its base provide rigidity, while reducing the number of Kevlar plys which must be used. The thickness of the helmet liner has been increased to provide improve headform acceleration performance, and to reduce unwanted reflections in the beamsplitter due to stray light originating from above and behind the helmet.

The Catadioptric system, shown in Figure 26, has a 10 percent smaller FOV than the Dual Mirror system, but provides much greater eye relief and improves image source transmission efficiency by a factor of three. The improved eye relief and image source/optics integration achieves a design, that permits the optics and image source assembly, to be detached from the helmet and stowed in the cockpit. Such a design prevents an expensive assembly from becoming a piece of personal equipment subject to greater abuse. However, this capability is gained at the expense of increased helmet weight and rotational moments, and stray light problems resulting from a large combiner/beamsplitter assembly located a relatively large distance from the helmet. Upward vision, in particular, is greatly restricted, to prevent severe overhead stray light problems.

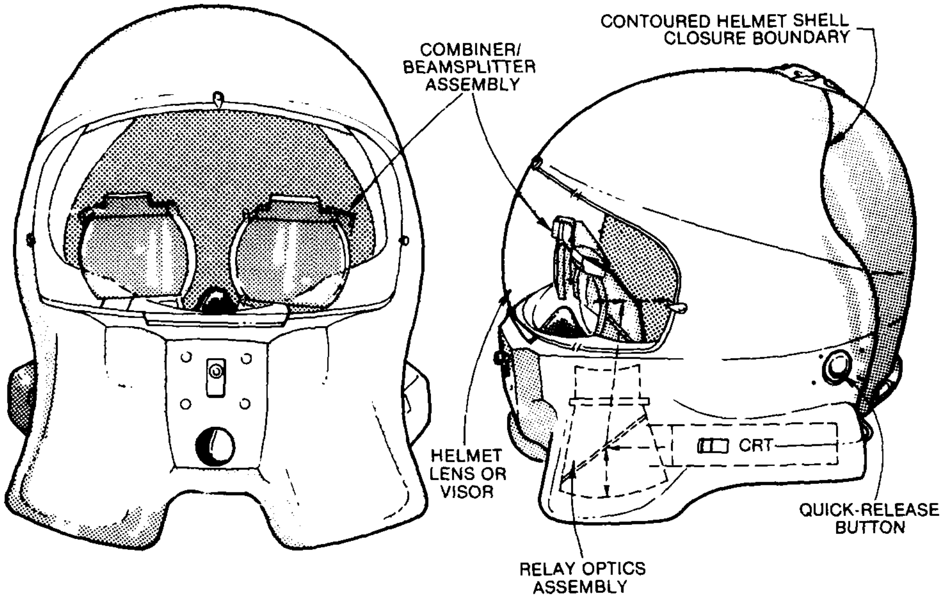


FIGURE 25
PROTOTYPE DUAL MIRROR OPTICS/HEADGEAR BREADBOARD

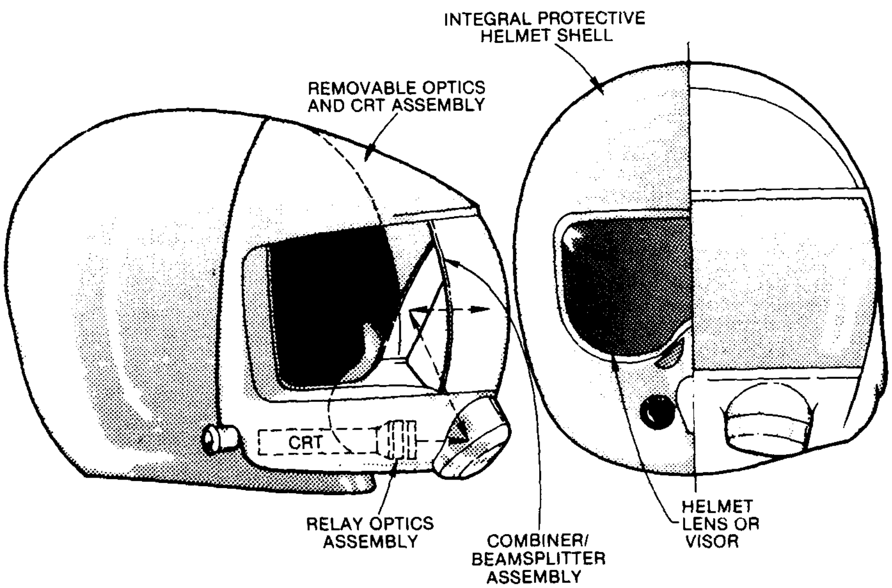


FIGURE 26
PROTOTYPE CATADIOPTRIC OPTICS/HEADGEAR BREADBOARD

The Off-Aperture system, shown in Figure 27, depicts yet another novel optical system/helmet design approach. This design locates the CRT image sources vertically, at the rear of the helmet, to improve the head/helmet CG characteristics. This location precludes a rear entry design, but its lack of direct involvement with the stabilizing oxygen mask permits the mask to be removable when the helmet system is worn. The design utilizes a high efficiency refractive optical design to transport the CRT image to the combiner mirror viewing surface. This permits achieving image source transmission efficiencies of 80 to 85 percent, and also allows greater ambient transmission, while providing good image contrast. Excellent eye relief and clearance are also characteristics of this design. However, system weight is high, although use of plastic optics and other system refinements could greatly improve this condition.

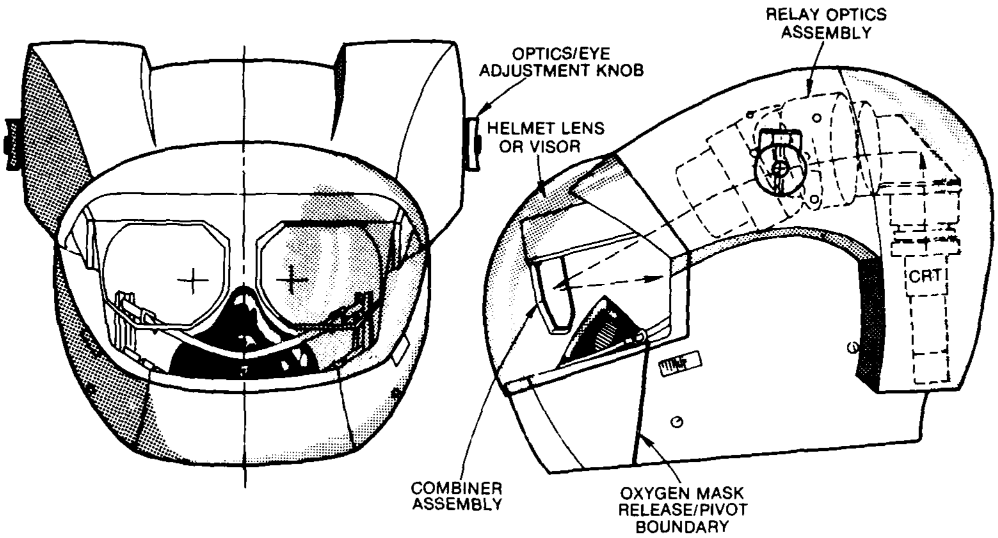


FIGURE 27
PROTOTYPE OFF-APERTURE OPTICS/HEADGEAR BREADBOARD

IMAGE SOURCE DRIVE ELECTRONICS

Although sometimes given secondary consideration, the image source or CRT drive electronics, which controls the binocular optics CRTs as shown in Figure 1, are extremely important components, for VPD HMD applications. Their performance is a fundamental factor in the modulation transfer function (MTF) that the CRT can attain. The drive electronics also control most of the important factors relating to the customization/integration of the CRT formats with respect to the optical design. For this paper, a relevant discussion of design issues need only concern itself with those factors, which are critical to the proper integration of the CRTs and their image formats, with the optics and headgear. The issues of greatest importance are felt to be:

1) CRT-to-optics mapping correction

2) Derotation

3) Electronic alignment

4) Other CRT X:Y Deflection issues

5) Power Supply performance

CRT-TO-OPTICS MAPPING CORRECTION

As the discussion associated with Figure 17 has already explained, the F-theta mapped optics produces a type of pincushion distortion which must be corrected by implementing barrel distortion of the CRT image format. As mentioned in [01,02], partially overlapped optics, which have their optical axes turned out, can also produce mild perspective distortion which is trapezoidal in form. Ordinarily, such distortions could be specified by the optical designer, and the system designer could insert the appropriate corrections using a truncated polynomial approximation with sufficient correction terms in dedicated correction circuitry associated with the deflection subsystem. However, given the variation experienced between individual CRT electron optics, the deflection yoke, and the physical alignment of the deflection yokes with the electron optics during the manufacturing process, these ideal conditions cannot be obtained. Therefore, each CRT must be calibrated for the particular HMD design, and the correction coefficients recorded and entered into the control elements of the CRT

electronics. Normally, correction terms to third order are sufficient, which is fortunate, since each additional order implies a commensurate increase in deflection electronics bandwidth [22]. The correction terms most often used are listed in Table 6. Their respective effects on the CRT's X and Y axis can be found in reference [07].

TABLE 6
CRT MAPPING CORRECTION TERMS

X-AXIS DEFLECTION	Y-AXIS DEFLECTION
$X^2, Y^2, XY^2, X^2Y^2, X^3, Y^3$	$XY, X^2, Y^2, X^2Y, X^2Y^2, X^3, Y^3$

DEROTATION

For HMD applications it is sometimes desired that the display format be maintained at the proper orientation with respect to the aircraft's or simulator's roll axis, regardless of the roll orientation of the head, and therefore, the display presentation. Maintaining the proper orientation is usually accomplished through the use of roll sensing provided by a helmet orientation/position measurement system whose roll output is fed directly to the drive electronics or, if a 2 or 3-dimensional graphics processor is being used, directly to that subsystem. As shown in Figure 6, for a partially overlapped, binocular system, the visual center of the optics is off center from the CRT, and the derotation to be performed involves both a translation and derotation on the CRT. Particular characteristics are set by the VPD design conditions. This correction must be performed at the field rate, at which the display is refreshed. The resolution to which this correction must be accomplished has already been discussed in sufficient detail in reference [22]. Due to noise and bandwidth considerations in the display deflection electronic's subsystem, and system implementation issues concerning the use of sensor systems, derotation of imagery is usually performed by the CRT electronics. Derotation of vector graphic symbology is best accomplished at its source, and then transmitted in corrected form to the CRT drive electronics.

ELECTRONIC ALIGNMENT

As previously discussed, some electronic alignment must be performed, to correct for residual errors in the alignment of the optics and in the reproducible characteristics of individual CRTs. Although complex alignment patterns have been employed to carefully check the exact horizontal/vertical alignment of partially overlapped binocular displays, the simple patterns shown in Figure 28a and 28b are usually sufficient. The pattern shown in Figure 28a has been recommended in the literature, however the pattern shown in Figure 28b appears to produce better results, because there are no identical structures presented to both eyes which the eyes might attempt to converge to identical retinal correspondence points. In addition, the pattern shown in 28b provides exact endpoint match capability, not provided by some of the open reticle patterns, which provide only horizontal lines to one eye and vertical lines to the other. Also, results obtained at AAMRL show that these patterns must be flashed in order to prevent improper convergence of the display. A duty cycle pattern that seems to work well is to repetitively flash the patterns on for about 75 milliseconds, followed by a 100 to 125 millisecond dark period.

OTHER CRT DEFLECTION ISSUES

In addition to issues relating to CRT X:Y deflection quality, a number of other issues are deserving of some discussion. Due to the high resolution magnified CRT format imposed by the VPD FOV conditions, where the same image point is transmitted to each eye through different portions of a partially overlapped optical system, on-axis deflection linearity is critical. Linearity is usually specified to be in the range of 0.5 to 0.25 percent. To achieve such linearity with miniature CRTs, a class-A linear deflection amplifier design is normally required. Class A amplifiers cause heat dissipation to become an important design issue. VPD CRT design which stresses higher acceleration potentials and, therefore, stiffer e-beams, exacerbates this problem. To support this performance, low capacitance cabling and low inductance/capacitance, high current deflection yokes using only ferrite cores are employed. These requirements, coupled with the desire to achieve small dimensional sizes for the electronics, often requires the use of conductive liquid cooling, rather than convective air cooling for the CRT electronics.

Also, as can be observed from Figure 6, the CRT is overscanned in the horizontal direction to (1) obtain the largest format possible for the normal 4:3 aspect ratio, and to (2) ease the optical design problem. To prevent damage at the edge of the CRT caused by electron beam heating, the beam must be blanked (turned off) automatically at a given radial distance, using an operating mode normally referred to as "circular blanking". The extinction of the e-beam is controlled by the magnitude ($|X+Y|$) of its radial distance from the deflection center of the CRT, based upon CRT quality area size and any additional deflection correction control that is active. There are several methods employed to accomplish circular blanking, however, methods that employ slow square root circuitry are to be avoided.

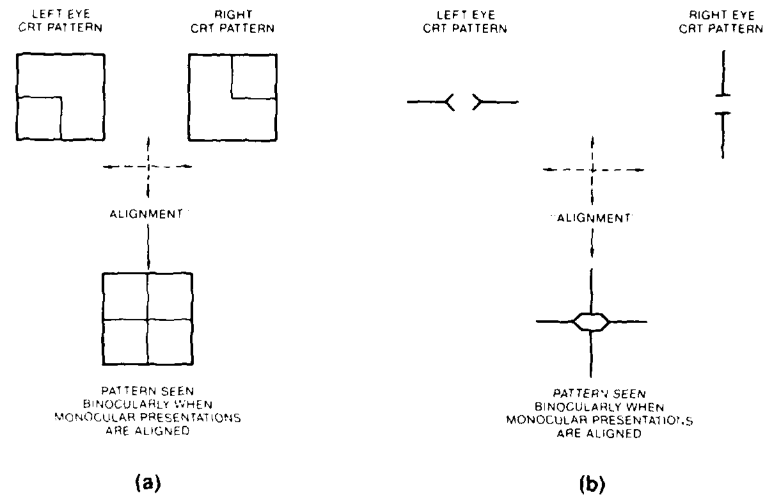


FIGURE 28
BINOCULAR DISPLAY ALIGNMENT PATTERNS

POWER SUPPLY PERFORMANCE

The HMD optics magnify the CRT faceplate imagery, from 8 to 19 times that of the original imagery. Magnifications of this order are sufficient to make electron beam spot noise, raster line jitter and drive electronics power supply noise both noticeable and objectionable. This makes power supply noise and regulation specifications very important.

The interaction of the CRT drive electronic's power supply noise and ripple with the display imagery, can produce complex effects. These artifacts produce movement of the display imagery visible to the human operator, depending upon their frequency and amplitude as a function of angular subtense on the display. This is particularly true for military power supplies, that utilize high frequency switching designs. As an example, consider the implementation of a 1225 line, 2:1 interlace scan format on an HMD with a 50 degree horizontal FOV. The scan line "on time" for a 1225 line rate is approximately 23.8 microseconds, which implies that one degree on the display equals about 0.5 microseconds. Since visual contrast sensitivity peaks at about 3 to 4 cycles per degree, a switching power supply with a ripple frequency of 6 to 8 megahertz has a switching frequency that could cause cyclical patterns where the eye is most sensitive. Alternately, a switching supply operating at 500 kilohertz, may be sufficiently removed, if ripple amplitude is low enough, to moderate such effects. The point here is that interactions of this type should be thoroughly investigated for all anticipated operating conditions.

The ability to obtain the needed performance is, in turn, dependent upon the specification of a reasonable set of CRT voltages, adjustment ranges for those voltages, and the maximum operating currents that are allowed. Table 7 provides a set of specifications for the latest CRT designs that provide operating margins which permit minimal power supply noise and regulation requirements to be met.

TABLE 7
CRT DRIVE ELECTRONICS POWER SUPPLY REQUIREMENTS FOR IMPROVED STD BIPOTENTIAL GUN CRT

PARAMETER	VOLTAGE VOLTS		CURRENT MICROAMPS		RIPPLE AND NOISE	REGULATION
	MIN	MAX	MIN	MAX		
ANODE (SCREEN)	10,000	13,500	0.0	300	≤0.05%	≤0.5%
G_3 (FOCUS)	1,000	3,000	0.0	1,000	≤0.05%	≤0.1
G_2 (ACCELERATOR)	500	1,500	0.0	100	≤0.05%	≤0.1%

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TOWARDS THE NEXT GENERATION FIGHTER COCKPIT: THE EAP EXPERIENCE

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SUMMARY

This paper outlines the main design of the cockpit of the EAP (Experimental Aircraft Programme) aircraft - a technology demonstrator produced by British Aerospace and Aeritalia in cooperation with the British, Italian and German Avionics Industries. The structured design process that was followed is described. The main features of the resulting cockpit are outlined, together with some of the rationale behind their design. These include:

- Display moding: how the format hierarchy is managed, how the formats were constructed and how colour has been used on the displays. A selection of the formats are illustrated and described.

- The Hands On Throttle And Stick concept and how this applies to the EAP.

- A Manual Data Entry facility capable of controlling ten different subsystems through totally multifunction devices.

- An intelligent warning system based on the use of a digitised voice.

These facilities have been flying for over one year now and the experience gained during their design and subsequent flight testing is helping to form the basis for the European Fighter Aircraft (EFA) cockpit design.

1. INTRODUCTION

In the late seventies and early nineteen eighties various European companies were pursuing national designs for a future fighter aircraft. In 1982 British Aerospace of Great Britain, Aeritalia of Italy and MBB of West Germany joined forces to investigate the possibilities of producing a joint specification to meet their individual national requirements. Work progressed over the next year on this collaborative aeroplane known as the Agile Combat Aircraft, A.C.A., with the intention of producing two demonstrator aircraft, one to be built in Britain and the other in Germany. However towards the end of 1983 Italian and German government support was withdrawn and work on the German aircraft was curtailed. The design of the remaining British demonstrator was rationalised and at the beginning of 1984 the project was renamed the Experimental Aircraft Programme or EAP. The project was jointly funded by British Aerospace and the British government with support from Aeritalia and the British, Italian and German avionics suppliers. Work progressed between these industrial partners over the next two and a half years to achieve a first flight of the EAP in August 1986. A photograph of the EAP aircraft can be found in Annexe 1.

The aim of the EAP was to integrate a number of advanced concepts and technologies into a single aircraft to demonstrate the feasibility of a high performance fighter of the 1990s. These concepts included:

- advanced structural design

- active control technology

- a utilities management system and an avionics system utilising a Mil Std 1553b data bus

- an advanced electronic cockpit

It is the description of this last point which forms the basis of this paper.

2. THE EAP COCKPIT PHILOSOPHY

The basic cockpit configuration can be seen from the diagram in figure 1. The twenty five degree ejection seat, providing a pilot back angle of twenty one degrees, faces a wide angle head up display and three full colour raster/cursive multifunction head down displays. These displays are used under normal conditions to present to the pilot all the information he requires to fly and manage the aircraft. However should there be a catastrophic failure resulting in the total loss of these displays, the pilot is provided with a suite of 'Get-U-Home' instruments which present the necessary flight reference, engine and fuel data via a mixture of display technologies, LCD, LED etc. Forming the left glare shield is a multifunction manual data entry facility to allow in flight

insertion/alteration of navigation, communications etc. data. Flight control of the aircraft is allowed by a centre pedestal mounted short stick, minimum displacement rudder pedals and linear slider throttles. This entire cockpit has been designed to be operable by a pilot falling within the three to ninety nine percentile UK and Italian pilot population.

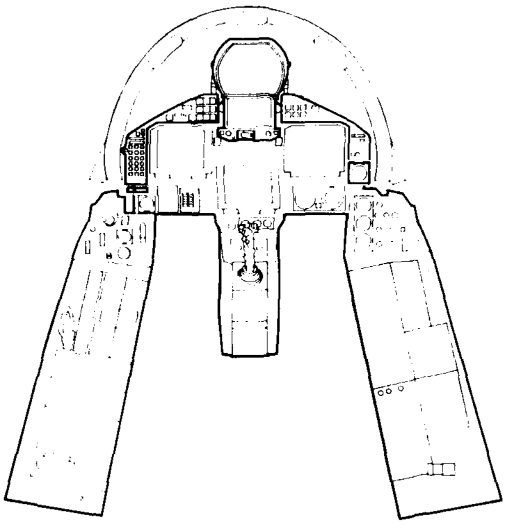

FIGURE 1 : BASIC EAP COCKPIT CONFIGURATION

The EAP is not a weapon system aircraft, it is a technology demonstrator, however it was the intention from the beginning that within the cockpit the concepts, in terms of the man machine interface, be developed with consideration of the implications of a full weapon system. The aim was to develop philosophies, for such things as moding the electronic displays and the warning system, which would allow future graceful expansion to include the greater complexity of a more sophisticated attack and identification system, without significant changes to hardware and with no change to cockpit operating philosophies.

The advent of high performance systems processors and the digital data bus, together with new cockpit technologies such as colour displays, multifunction panels and digitised voice, meant that the potential design that could be achieved, in terms of flexibility, was staggering. However equally staggering was the potential to create an unmanageable cockpit caused by 'technology gone mad'.

It was this fear of 'technology gone mad' which made it essential that the ergonomic aspects of the design should be considered at all stages and in fact ergonomic implications formed an integral part of the design process.

This design process followed a top down structured approach that began with Mission Analysis. The Mission Analysis provided the bulk of the raw material required for the detailed moding process, however before the detailed moding began various cockpit philosophies were written which set out the principles behind the cockpit design. Such philosophies are necessary to establish a basis for the cockpit design that ensures that the subsequent detailed design, which involves greater numbers of people, follows a consistent and logical path. On EAP they were of additional value to establish basic principles for the implementation and integration of the new technology into one cockpit - something that was necessary due to the lack of practical experience that was available. These philosophies covered:

- Display Moding
- Hands on Throttle and Stick
- Manual Data Entry
- Warning System
- Cockpit Layout
- Lighting
- Colour
- Get-U-Home

These cockpit philosophies were a fundamental first step, however they were theoretical and it was considered that an important factor in trying to design a cockpit for pilots, rather than engineers, was to adopt an empirical approach. Therefore the principles outlined within these philosophies were soon manifested into various forms of simulation, the main vehicles being a static cockpit mock-up facility and an active cockpit.

The static mock-up (see photograph in Annexe 2), was a wooden cockpit which formed an accurate representation of the current aircraft lines. It was used extensively to design and evaluate the cockpit geometry and layout - the hardware aspects of the man machine interface.

The active cockpit (see photograph in Annexe 3) on the other hand provided a functionally representaive simulation of the cockpit displays and controls and was used more to develop the software driven aspects of the cockpit. Initially local simulations were produced of, for example, the Manual Data Entry Facility or the Warning System and these were assessed in isolation. Once these individual aspects were considered satisfactory they were driven dynamically, backed up by simulations of the various aircraft subsystems and the outside world. At this stage the various elements (formats, warnings, layout etc.) were brought together and the overall moding assessed during part and full mission simulation. Throughout all these stages the simulations were feeding into the design process. This is perhaps one of the biggest lessons which can be learned from the undoubted success of EAP - that is that facilities, such as static and active cockpits, be available at a sufficiently early stage in a project to have an impact on both the hardware and software specifications.

It is the design which initially resulted from these philosophies and that was developed and refined through practical experience in the various simulations, that forms the EAP cockpit as presented on the following pages.

3. DISPLAY MODING

All the main flight reference, navigation and systems information on EAP is presented to the pilot using electronic displays, in the form of a Head Up Display (HUD) (30 x 20 degrees) and Multi Function Displays (MFD) (154 mm x 116 mm) head down.

In order to successfully integrate these displays within the overall cockpit moding, certain aims were established early on in the EAP programme. These aims were:

- To present information to the pilot in a relatively simple manner. The pilot in the midst of a demanding mission cannot be faced with an overly complex picture and symbology, but requires fairly obvious and straightforward information.

- To display what the pilot <u>needs</u> to know. This does not mean solely that information relating to functions under pilot control. It is important that the pilot always has a mental picture of where he is - both within the outside world scenario and within the various cockpit processes. The information presented on his displays should provide him with this impression so that he can assume the role of an overall manager.

- To make the overall structure of the format hierarchy easy to manage. It could be very easy, with a suite of multifunction displays which are capable of providing a multitude of formats, to produce a format hierarchy in which the pilot could get lost - not knowing where he is in a tree or how to get to the particular format he desires. This was prevented on EAP by making all information available with no more than two button presses and essential information available with no more than one button press.

These aims gave rise to the development of the principles of format management, format construction and colour usage as described in the subsequent sections.

3.1 FORMAT MANAGEMENT

As one of the prime aims of the display moding task was to produce a manageable format hierarchy, a system was developed for EAP which could be extended to also satisfactorily accommodate future weapon system formats. Some of the methods used to manage this hierarchy are as follows:

- Various phases of flight were identified, e.g. Ground Procedures, Take Off, Navigation, during which the pilot requires different types and levels of information. The pilot has the facility to select the phase of flight he desires and the system then presents on the displays that information he needs to carry out that phase of flight.

- Dedicated push buttons are provided on the multi function displays to allow direct selection of certain important formats.

- A dedicated push button is available (PRE), on each multi function display, to allow direct selection of the format that was presented before the currently displayed one.

- A dedicated push button is available (NRM), on each multi function display, to return to the format that is normally presented on that display for the particular phase of flight.

- A dedicated push button is available, on the stick top, to directly call up on to the head down displays information to allow the pilot to recover the aircraft attitude from any unusual positions.

- A soft key is always available, in the same position on each format, to allow the pilot to step through all the formats in a predefined sequence.

- The title of each format is always presented in the bottom right corner of each format.

3.2 FORMAT CONSTRUCTION

To ensure usable displays, rules applying to the detailed design of the formats were determined. The following are some examples:

- All symbology on the EAP displays is drawn cursively, thus providing clear symbols and smooth lines, whatever their shape or orientation. To ensure adequate visibility the minimum character height was defined as 3.6 mm, with special emphasis being provided by characters of 4.8 and 6 mm. These sizes represent 17, 22 and 28 minutes of arc respectively when viewed in the EAP cockpit and provide good readability in the environment.

- To ease any potential problems the pilot might have in locating information on the formats, it was ensured that wherever the same information is presented on a different format it is presented in the same position. For example, whenever heading information is presented, either head up or head down, it is presented at the top of the format in the centre.

- On the EAP the control inputs are either initiated manually by the pilot, using soft keys around the displays or on the manual data entry facility, or automatically by the system. To ensure that the pilot is always aware what is currently selected, a selected option is always indicated by the appropriate legend on the display being boxed.

3.3 COLOUR PHILOSOPHY

One of the main factors which distinguishes the EAP from other military aeroplanes is the full colour capability of the three head down displays. An extensive colour philosophy has been developed, based on theoretical and experimental concepts, the principle aim of which is to use colour for functional rather than purely aesthetic purposes. This does not in any way mean that the aesthetics of the formats were disregarded, only that this took second place to consideration of the functional use. To meet this design aim the majority of human factors research recommends a limited use of colour in order to decrease the probability of habituation and hence increase the attention getting qualities of the colour when it is present. Starting with this, the approach taken was to initially consider the formats as achromatic and then add colour in line with the colour usage philosophy.

It was considered that the use of colour on the displays should always have a task related meaning, and be used in areas to maximise its effectiveness, such as:

- to provide realism, e.g. on an attitude format for sky/ground.

- for cueing or alerting to critical features, e.g. high priority threats, scales exceeding limiting values.

- where strong associations already exist with a colour, e.g. green, red, amber.

- for relating important similar information on a cluttered format.

- to allow a distinction between symbols on scales which are located together.

- to provide contrast between a sensor video picture and overlaid symbology.

N.B. It should be noted that while the benefits of colour were exploited other 'coding' methods were also continued, such as shape and position coding.

Within this general usage philosophy, specific colours were used as follows:

WHITE: Basically all symbology started off as white and was then coloured as necessary. Two whites have been used, a Bright White and a Dull White. The Bright White is the most visible of all the colours under all ambient illumination conditions and has been used for all changing or dynamic symbology and alphanumerics. The Dull White, while still quite visible, does not appear as compelling as the Bright White and tends to appear more in the background. This has made it a most suitable colour for symbols or alphanumerics that are fixed values and/or do not change their position.

GREEN: Green has been used where a positive good or go indication is required. In addition it was also used on the Horizontal Situation Display (HSD) as a trial to see if the format would benefit by linking together all the navigation information relating to where the pilot should be flying. This has proved to be very useful in flight.

RED: Red has been used only when related to red warning situations or threats. In order to retain the impact this colour can have, it only appears when the 'red' situation is reached, e.g. there is not a red zone permanently shown on the engine temperature scales indicating overtemperature - they turn red only when warranted by the situation.

AMBER: Amber has been used only when related to amber warning situations or certain threats. As described for the colour Red, Amber only appears on the format when it is required.

BLUE: Blue was shown not to be a very compelling colour and was basically used in two ways. It was used as an infill to provide realism to a format, for example to represent the sky on an attitude format or to represent the fuel in the format showing the aircraft fuel tanks. Alternatively it was found that Blue could be quite easily deliberately ignored when looking at a format so that any lines drawn in blue could be seen if required or if necessary they could visually fall into the background and not be noticed. This use proved convenient for drawing demarcation lines on a format or even for drawing range scales which could be quite numerous on a format and hence potentially distracting.

CYAN: Cyan, or sky blue, is the only colour used which can sometimes be confused with other colours, i.e. in high ambient with white and at the low ambient end with green/blue. However it proved to be a good bright and visible colour. It was decided therefore to use it for those instances where the actual colour used was not important but it was felt the information concerned would benefit by being a different colour from the information around it to allow visual discrimination.

BROWN: Brown has only been used to provide realism on the attitude format by representing the ground.

In practice the use of colour on the MFD has proved successful on EAP. When problems are indicated on a format the pilot can very easily and rapidly identify the area of interest.

The principles and techniques described in the previous sections resulted in a suite of thirteen formats. The next section outlines a selection from these formats.

3.4 THE FORMATS

STATUS

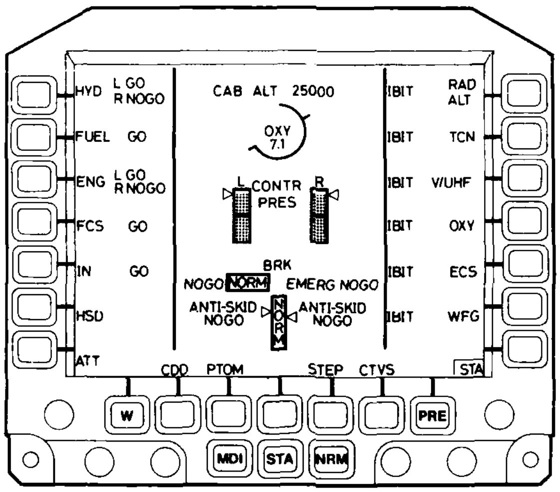

FIGURE 2 : THE STATUS FORMAT

The Status format presents, on one surface, essential information on the health of the various aircraft systems, to save the pilot the task of paging through the individual systems formats. An important use of this format is on the ground, during aircraft start up. With it the pilot is provided with much of the information that he requires to initialise the aircraft and prepare it for flight. It supplies him with information on the state of various systems such as hydraulics, fuel and the engines and tells him if these

systems are 'GO' and therefore ready for flight. The Status format also provides the pilot with the facility to initiate, if required, the pre flight tests on various subsystems such as Oxygen or the TACAN and presents the results, in the form of a 'GO' or 'NO GO'. Individual test selection in this way is considered acceptable for EAP, however for an inservice aircraft it will be desirable to initiate all such tests with a single key.

In addition the Status format is used as the hub format to the entire format hierarchy and as such it provides direct access to all the other formats with one button press.

PRE TAKE OFF MONITOR (PTOM)

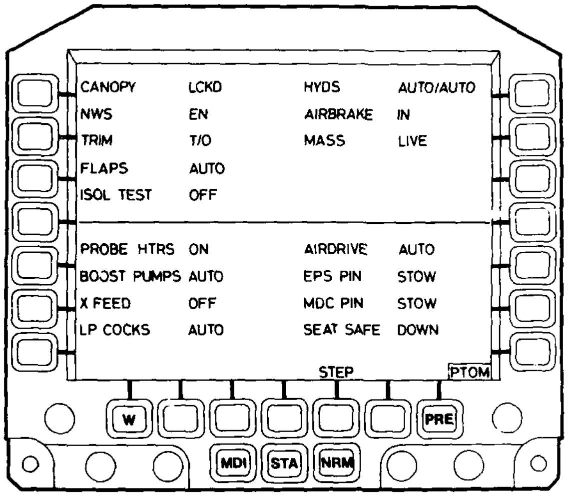

FIGURE 3 : PTOM FORMAT

While the Status format is used throughout the ground procedures the PTOM is called up just before take off as a last check that the aircraft is correctly configured. This format acts as a form of electronic checker that tells the pilot that any manual selections under his control have been appropriately selected for take off, this applies to such things as airbrakes, canopy, nosewheel steering etc. Full use is made of colour coding on this format. The status indications, that is whether the canopy is locked or unlocked, the nose wheel steering is engaged or disengaged etc., are written in green for GO or red infill for NO GO for take off. The pilot then basically looks to the format expecting to see all green - he does not actually have to read anything - and if anything is highlighted in red he knows that one of the pre flight actions has been forgotten. Such a format is seen as essential for an operational single seat cockpit, where the pilot does not have a second crew member to prompt or remind him of necessary pre flight actions, but where the pilot must remember for himself what must be done.

ENGINES

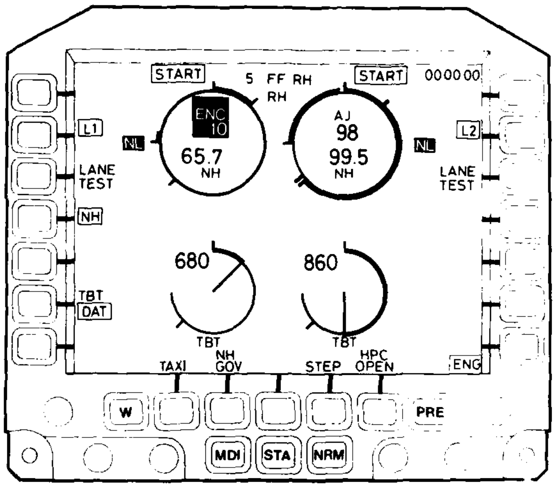

FIGURE 4 : THE ENGINES FORMAT

The Engine format presents digital and analogue information on a variety of engine parameters, for both left and right engines, on one compact format. Engine speed and nozzle area have been combined on to a single scale as, although these parameters are unrelated in engine terms, to the pilot they indicate the thrust level of the engine. Some engine control is provided by the soft keys and those controls that should only be used on the ground are occulted from the format, and the function deenergised, in the air.

HYDRAULICS

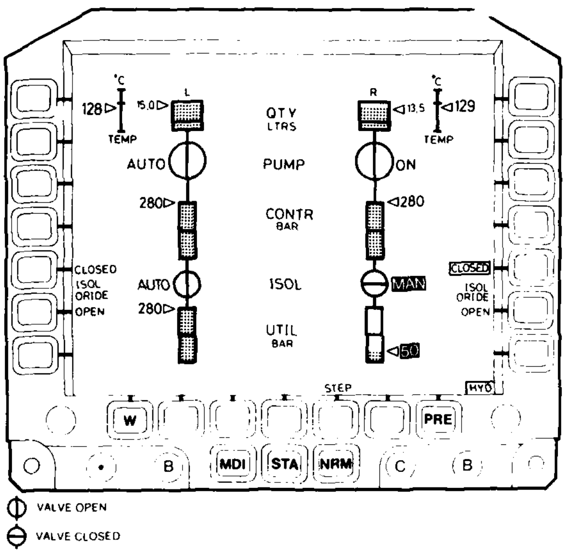

FIGURE 5 : THE HYDRAULICS FORMAT

The Hydraulic format comprises two schematics which represent the left and right hydraulic system. Each schematic includes scales and indicators to present information on pump and valve positions, pressure indications etc. Again the basic presentation of the format appears green and white when the systems are GO and areas of red appear surrounding indications of any faulty or dangerous situations. As with the engine format, the analogue indications are supported by digital values or word captions as appropriate. Of interest on this format is the way the digital read outs move alongside their associated arrowheads on the analogue scale. This serves to reinforce the position of the arrowhead - making it more obvious and provides the digits themselves with a kind of analogue cue by their position along the scale. Because the scales are all relatively short and none of the arrowheads move at a particularly fast rate, there are no problems with locating and reading the digits.

FUEL

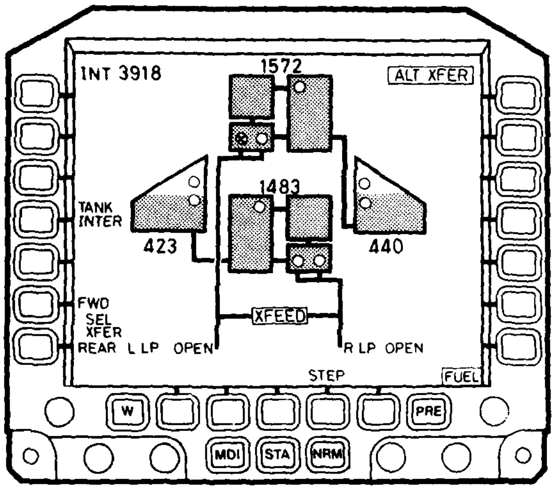

FIGURE 6 : THE FUEL FORMAT

This format represents, in pictorial form, the layout of the fuel system on EAP. Soft keys also provide the necessary control over the fuel system. The tanks are infilled with blue and the level of this infill in each tank descends as the fuel level decreases. Pilots have felt that this presentation of fuel quantity gives a good clear picture, at glance, of how much fuel there is in total on the aircraft. Digital readouts are provided of the exact quantity of fuel in the main tank groups. Transfer and boost pump states are indicated in the appropriate tanks.

ATTITUDE FORMAT

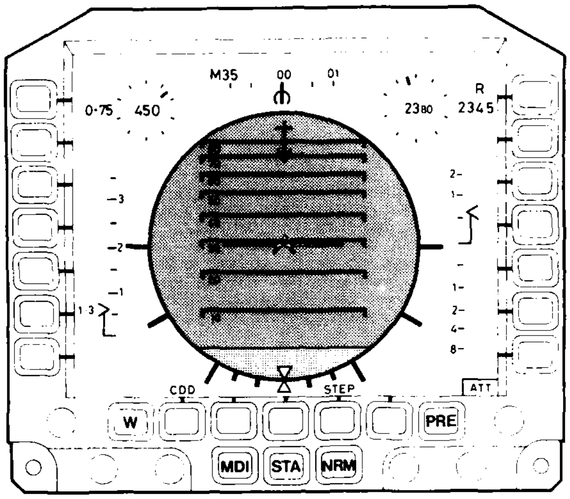

FIGURE 7 : THE ATTITUDE FORMAT

The Attitude format presents similar information to the HUD, in a head down situation. The coloured blue/brown ball mimics a conventional attitude instrument, however the presentation here is deliberately kept similar to the HUD to allow very easy transfer between the two displays. As this is an electronic display, the pitch information can be sourced to present either attitude or climb dive information, as preferred by the pilot. As well as being available from a soft key, this format can be selected via a stick top control, on to the multifunction display. This HOTAS function allows the pilot to immediately call up sufficient information to recover the aircraft, to straight and level flight, from any unusual attitudes.

HORIZONTAL SITUATION DISPLAY (HSD)

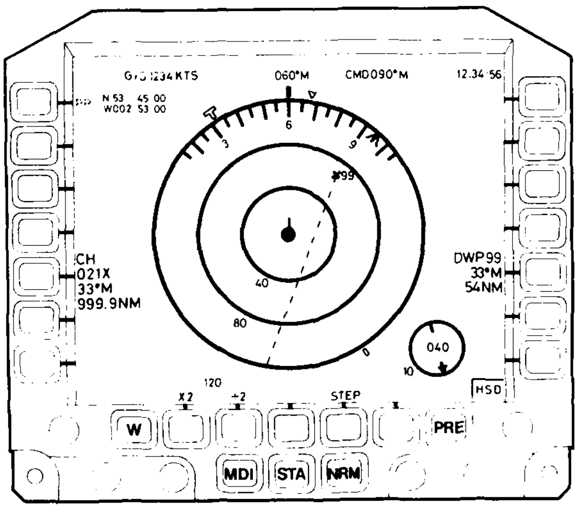

FIGURE 8 : THE HSD FORMAT

The HSD provides navigational information based on a compass rose format. As well as an indication of own heading and track, direction to the next waypoint and TACAN beacon are provided against the rose. Each of these symbols have been carefully drawn so that they can be easily distinguished from each other and if they are positioned over each other they can still be individually identified. Own aircraft position is indicated at the centre of the display and the position of the next waypoint in the route is indicated relative to that. Additional information around this centre compass rose includes at the top some details on own aircraft, on the left details on the selected TACAN beacon and on the right details of the destination waypoint and an indication of wind speed and direction.

4. HANDS ON THROTTLE AND STICK (HOTAS)

The Hands on Throttle and Stick (HOTAS) concept is considered to be fundamental to the cockpit design of our next fighter aircraft and as such has been catered for in the EAP design. Because EAP is a demonstrator the combat/sensor related controls are not active, but the design proceeded in this way mainly as an exercise to gain experience in the hardware design process and also to test, in the air, just how far the concept can be practically and usefully extended. Candidates for HOTAS on EAP were considered to be those functions which the pilot needs immediate access to during high workload and stressful mission phases, such as combat, and those functions to which the pilot frequently requires immediate access.

Results of mission analysis and detailed design indicated a high number of controls as candidates for inclusion on the HOTAS. This necessitated a particularly good design of the Throttle and Stick tops, which could physically satisfy the full percentile range to which the EAP has been designed and which also could allow the pilot to know, without hesitation, the exact position of the control he requires at any one time. This design was achieved as follows:

- A good basic shape was first derived which enabled comfortable positioning of the pilots' hands and arms.

- Having determined the required functions, they were allocated to which was considered to be the most appropriate platform, i.e. throttle or stick. In general, weapons related controls were allocated to the stick and the sensor related controls to the throttles. In addition, conventions, where they existed, were respected, e.g. airbrakes to throttles, trim to stick top.

- Functions were next allocated to control types, e.g. push button, toggle action etc. To aid in absolute identification of control functions different 'tactile' tops were used for many of the controls. This was considered to be particularly important for controls operated by the thumb, as generally a finger would be used to just operate one control but the thumb, being more dexterous, was allocated with several controls and thus their identification could be aided by shape coding. A basic design premise at this stage, aimed at reducing pilot mental workload, was that there should be no multi functioning of HOTAS controls used in the air.

- Controls were then positioned taking into account how accessible a function should be, how frequently it would be used, any necessary sequential operation with other controls and allocating the control to the digit which would be best suited to its operation.

This entire HOTAS design process was extremely iterative, starting with Plasticine models in a static cockpit mock up, progressing on to wooden mock ups and then finally metal models in an active cockpit facility. A diagram of the final items, showing the distribution of controls, is figure 9.

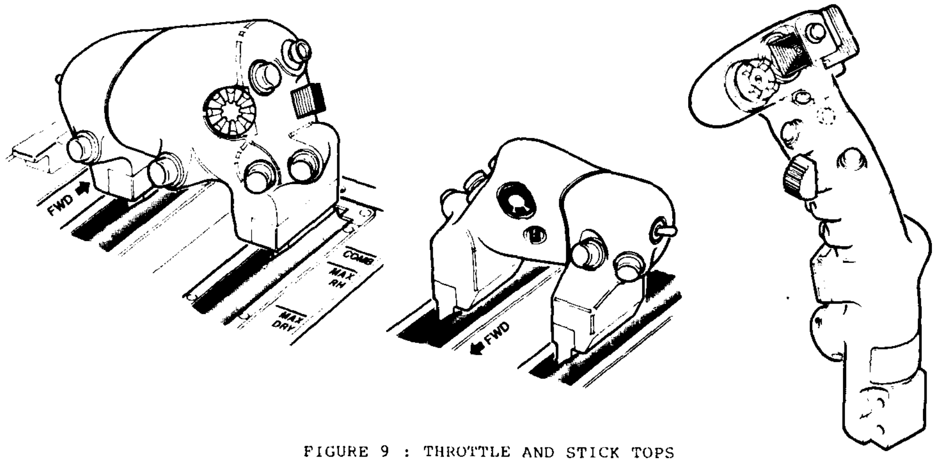

FIGURE 9 : THROTTLE AND STICK TOPS

5. *MANUAL DATA ENTRY*

It is now well accepted that the single seat cockpit creates the need for arranging the data entry controls for the various aircraft subsystems (*traditionally* scattered on the side consoles or other head down locations) in an operationally acceptable manner in a centralised and relatively head up location. To permit this on EAP, a single integrated keyboard facility was developed and this forms the *left hand glareshield area of the* cockpit (see figure 10). This allows easy head up operation by the pilot - providing a good steady platform for the *arm and hand* under vibration conditions and yet causing no visual obscuration to the displays during operation of the keyboard. To complement this concept the right glareshield contains dedicated read outs associated with data entered through the Manual Data Entry Facility.

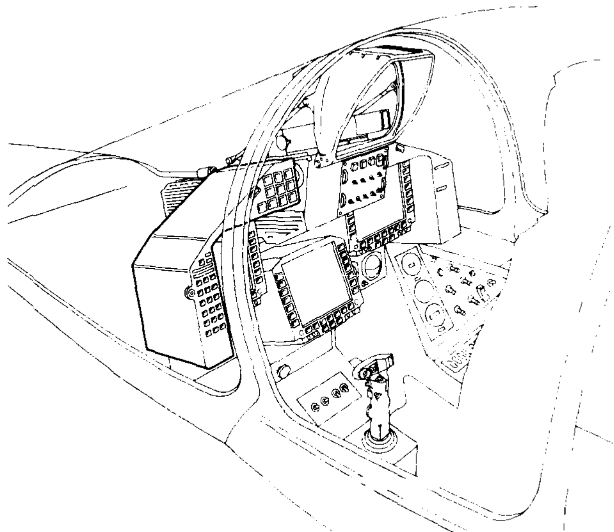

FIGURE 10 : INSTALLATION OF MDE IN THE COCKPIT

The type of data to be manually inserted or altered on the MDE on an operational aircraft would include:

a) Navigation data: waypoint data (latitude/longitude, UTM, Georef, elevation, time on waypoint etc.)

b) Navigation aids: TACAN channel and mode

c) Navigation modes: route planning and update

d) Communications: radio channel/frequency selection, modes (e.g. V/UHF, antenna selection, bandwidth, secure speech modes)

e) IN alignment modes

f) Time (system time, GMT)

g) Engine placard data

h) Identification system: IFF/NIS codes and modes

i) Defensive Aids Subsystem: Chaff/flare dispense programmes, modes etc.

j) Armament System modes

k) Data Link (e.g. JTIDS): modes, message input etc.

l) Landing Aids: MLS channels and modes etc.

Realisation of the virtual crew work station has to date been hindered by the level of technology required to support the system. Only recently has the technology been available to sense head position sufficiently accurately, in conjunction with advanced real-time graphic systems, to produce the required presentations. For airborne applications, size and weight are of particular importance.

The concept of a virtual work station is extremely straight-forward. The operator is presented with a computer generated representation of his control area, such as a control panel complete with switches and

At this moment only items a) to f) are implemented on the EAP, however, as with the entire cockpit design, the hardware and moding concept could encompass the remaining items with the necessary software.

The amount of data to be controlled by the facility and the fact that the hardware occupies a relatively small area of the cockpit, leads to the requirement for many of the controls to be multi function. However this has not created any problems with the final design, as experience has shown it is easy to learn how to operate the unit and it has proved to work well in flight. The following is a description of the facility which should be read in conjunction with figure 11.

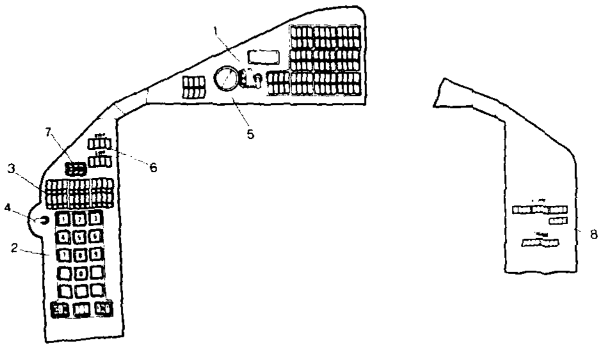

FIGURE 11 : MDE LAYOUT

System Selection and Moding Keys (SSMK) (1): Multi functioning of these keys is allowed by the fact that each key head legend comprises two rows of four 7 x 5 dot matrix LED symbols. In the first instance these keys are used to select the appropriate system, e.g. communications. When the required system has been selected, the legends on the keys change to present any moding options that are available for that system, e.g. for communications this could include bandwidth selection. Additionally, at this time these keys also allow the pilot to state the type of data he wishes to enter (if any choices exist), e.g. for communications he has the choice to enter either a manual frequency or alter the frequency against a preset channel. Whenever the keys are configured to this moding level one of the keys is always reserved as a reset function to return the entire keyboard back to allow system selection.

Data Entry Keyboard (DEK) (2): As soon as a system has been selected on the SSMK, the DEK is configured as appropriate to input the necessary alphanumerics. Thus with the above example of communications, to insert a radio frequency a 0 to 9 keyboard will be presented, however to insert a waypoint coordinate in UTM the appropriate alpha or numerical keyboard will be presented as required.

The multifunctioning of this keypad is made possible by a single 7 x 5 dot matrix LED symbol within each keyhead.

Read Out Lines (ROL) (3): Once a system has been selected on the SSMK, the ROL will reflect the data that is currently stored within the aircraft against that system. Therefore with the Communications system key selected and with the manual frequency moding key selected, the ROL will display the manual frequency that is currently stored within the radio. As the pilot then changes this frequency using the DEK, this new frequency will be reflected in the ROL.

Each of the two ROL comprise twelve 7 x 5 dot matrix LED symbols. Underneath each symbol is positioned a writing marker which illuminates as appropriate to indicate where the next character, inserted via the DEK, will appear.

Writing Marker Toggle Switch (WMTS) (4): Under normal operation the writing marker will automatically move along the ROL to indicate where the next character inserted via the DEK will appear, however for error correction purposes the WMTS is used to manually move the writing marker to position it below the character the pilot wishes to alter. Movement of this spring loaded toggle switch to the left causes the writing marker to move to the left and vice versa for movement to the right.

Communication Channel Selector (CCS) (5): The CCS allows selection of any radio channel and direct selection between a preset or manual frequency at any time, irrespective of current SSMK selections.

Waypoint Indicators (6): The Destination WayPoint (DWP) window indicates the waypoint which the aircraft is currently flying to and the Set WayPoint (SWP) window indicates the waypoint which follows the DWP in the route. During waypoint data entry the SWP window is also used to display the number of the waypoint on which the pilot is currently working.

Change Destination (7): This push button is used to enter the set waypoint as the new destination waypoint. This control can be operated at all times irrespective of what is selected on the SSMK.

MDE Memory (8): The MDE memory provides a permanent read out of data and moding selections that have been made using either the SSMK or the DEK. This ensures that regardless of what is selected on the SSMK at any one time, the pilot can always be sure, at a glance, of how the various MDE controlled systems are moded.

Annexe 4 provides an example of how the MDE can be used to input a manual radio frequency.

6. THE WARNING SYSTEM

It was clear from the beginning of the definition phase of the EAP project that a basic principle in an advanced aircraft was the necessity to relieve the (single) pilot from the burden of dealing with health monitoring of on-board equipments, sub systems and systems. In addition, in order to limit the pilot workload following an on board failure or external hazardous situation, an 'intelligent' warning system was required. Following these basic requirements, a health monitoring and warning philosophy was developed which provided under normal operating conditions automatic health monitoring through equipment, sub system and system continuous or interruptive BIT facilities. Adoption of this philosophy requires that, where practical, detection and diagnosis of a fault and correction of that fault automatically takes place without pilot intervention, with the pilot being involved at the diagnostic and/or corrective stage when the nature of the fault requires.

Analysis of more traditional warning systems showed a lack of consistency in handling and presenting warning type information. Where often a cockpit might contain a central warning panel and attention getting (or master caution) lights for the majority of warnings, several other warnings would still have their own unique indications or tones or perhaps a retrofitted 'voice'.

On EAP the basic philosophy is that the warning system is there to alert, inform and advise the pilot (rather than startle, confuse and mislead!). It was the intention that any 'failures', procedural or systems related, should be handled by the warning system and the plethora of odd lights or tones be replaced by a consistent approach.

The first step in developing the warning philosophy was to define the different categories of warning, as follows:

Category 1: This is a procedural warning that is notification to the pilot of a hazardous situation that requires immediate action, e.g. missile approach warning.

Category 2: This is a systems warning which is traditionally known as a red warning. It is notification to the pilot of a primary failure that requires immediate action, e.g. engine fire.

Category 3: This is a systems warning which is traditionally known as an amber warning. It is notification to the pilot of a primary failure that requires attention, e.g. failure of normal brake system.

Category 4: This is advice or information to the pilot of a procedural nature, e.g. 'Chicken fuel'.

In presenting these categories to the pilot the following media have been utilised:

Visual attention getters

[illegible] mounted in the head up area, which flash as soon as a warning [illegible]. They incorporate a press button function which can be pressed to allow the pilot to indicate that he is aware of the warning.

Attensor

An attensor [illegible] specially designed to be tailored to the [illegible] and as such does not have to be loud to be heard [illegible]. An attensor is used to alert the pilot to the existence of a warning and to indicate its category.

Digitised Voice

A digitised female voice is used to inform the pilot as to the exact nature of the warning situation. In the case of category 1 warnings, where reaction time is critical - up to a few seconds - the voice message takes the form of a command to the pilot, e.g. "Break right"; for the other categories the voice states the problem, e.g. "Left Hydraulics over temperature". To prevent excessive use of the voice and potential overload of the

pilot's aural channel, in the case of category 2 and 3 warnings the voice is only used to inform the pilot of primary warnings.

- Multi Function Display

  - A warning caption is presented on the multi function display format to visually inform the pilot as to the nature of the warning situation. Colour (red or amber as appropriate) is associated with these captions and the captions are positioned to indicate a left, right or neutral system. The background to the caption is flashed to indicate the most recent warning. On a full weapon system aircraft, where display space is at a premium, this function would be transferred to a separate warning panel.

- Pilot's Reference Cards

  - Traditional use is made of the flight reference cards to provide the pilot with advice on procedures and consequences following a warning situation. It is envisaged that the next stage from this is to make similar information available on a MFD.

- Get-U-Home Warning

  - In the event of a data bus failure the facilities of the main warning system are lost, and the pilot relies on what is referred to as the Get-U-Home warning system. This presents a limited number of high priority warnings that are independent of the data bus. As the MFD are lost with the bus, their function, in terms of presenting warnings information, is replaced by the Get-U-Home warning panel.

It should be noted that early flying of EAP did not evaluate this full warning system - this is planned for the next phase.

7. TO THE FUTURE

So this has been the 'EAP Experience', an experience that started with the basic principles, developed through simulation and pilot involvement and has, since the first flight twelve months ago, been flown by ten British and Italian pilots and evaluated by many more on the ground. (A photograph of the final cockpit is Annexe 5).

But has it been a worthwhile experience?

In the eyes of the pilots most definitely. The entire aircraft, including the cockpit, has received a favourable critique and the pilots certainly have no problem flying it - in the three months from the first flight, fifty two flights were completed by seven different pilots and the second phase of flying brought sixty four flights in just sixty eight days! And it seems that despite the change in technology that EAP represents over traditional cockpits, pilots can very easily train on how to operate it - it takes just three days for a visiting pilot to master the entire aircraft, including the cockpit and its associated procedures. It is described as being simple, straightforward and enjoyable to use.

It has also proved a worthwhile experience from a cockpit designers point of view. There is now confidence that a full weapon system cockpit along the EAP lines will work; it has been shown that facilities such as data entry, warnings and utilities management can be designed and integrated within the cockpit in such a way that they need not take priority in the pilots span of attention - they can become background and routine facilities to the pilot so that he may concentrate his effort on being a weapons manager.

To this end the EAP cockpit has formed an admirable basis for work on the European Fighter Aircraft (EFA). An important aspect of this is the fact that within the design team there are now people in the unique position of just having designed and built one aircraft and now they are immediately starting on the next, without a significant time gap. Indeed the benefits of EAP will continue, as new concepts are evolved on it in further trials; initially this will involve incorporation of the full warning system and control by the use of Direct Voice Input (DVI). Thus it is hoped that building on this very recent experience with the EAP we shall be able to work towards the next generation European cockpit.

8. REFERENCES

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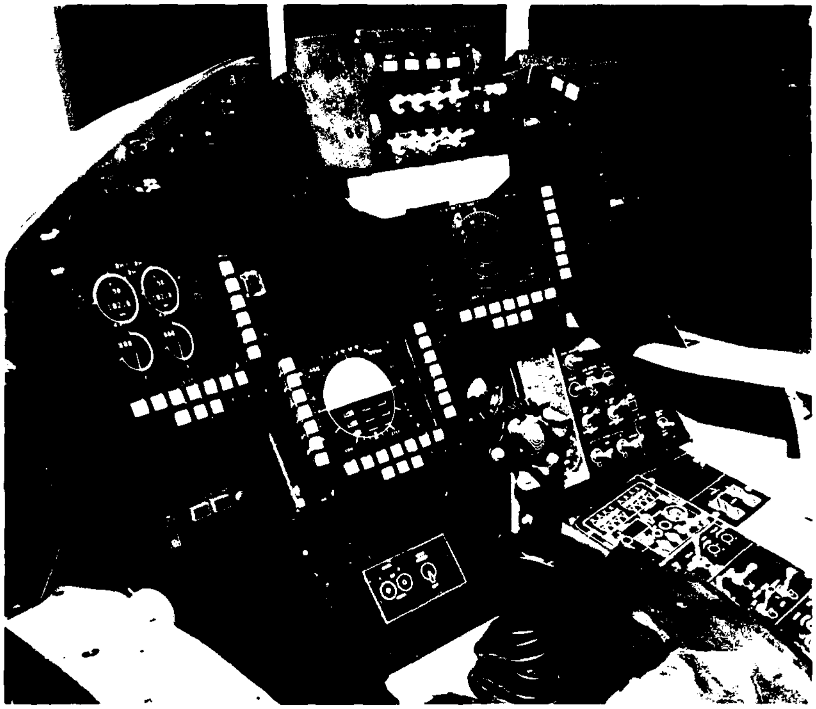
9. ACKNOWLEDGEMENTS

The authors wish to express their thanks to the other members of the EAP Cockpit Group and all of the people involved in the systems design of the EAP.

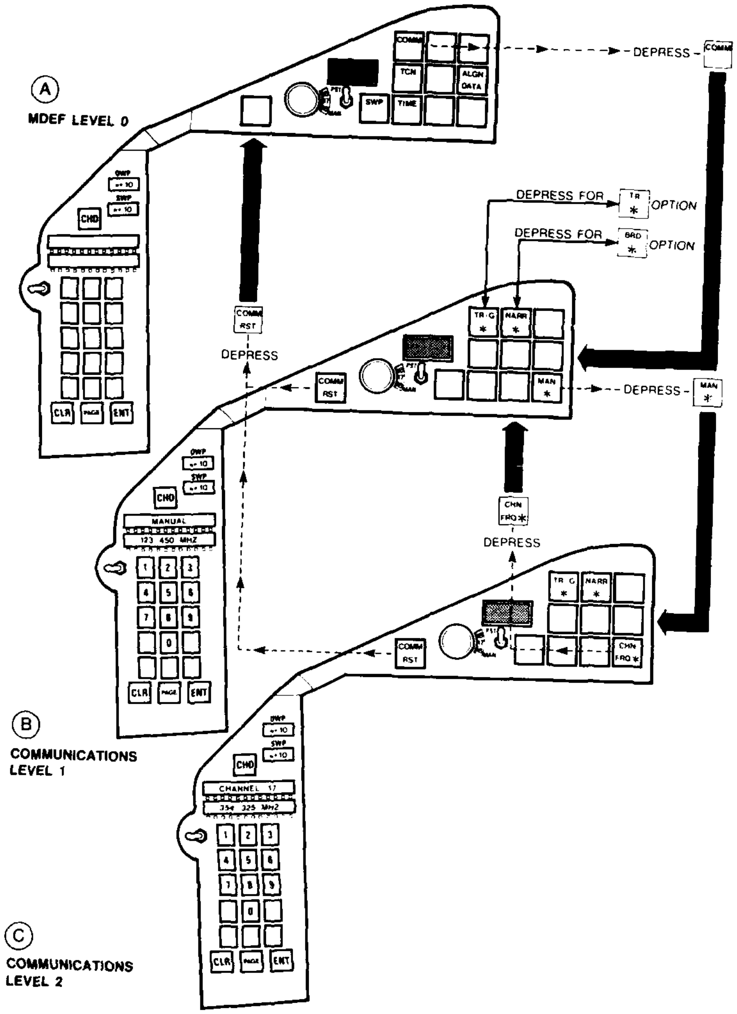
This work has been carried out with the support of the Procurement Executive, Ministry of Defence.

ANNEXE 1 : THE EAP IN FLIGHT

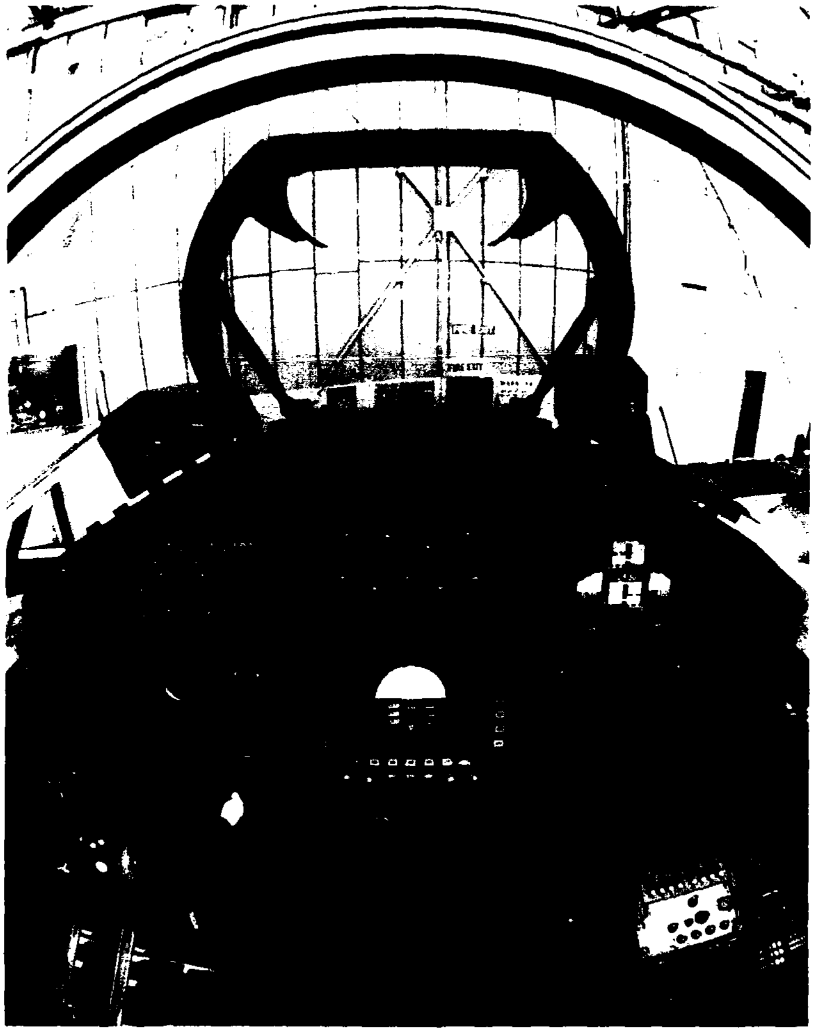
ANNEXE 2 : THE EAP STATIC MOCK-UP
(PHOTOGRAPHED DURING A SIMULATED EJECTION TRIAL)



ANNEXE 3 : THE EAP ACTIVE COCKPIT



ANNEXE 4 : TYPICAL MDE PROCESS



ANNEXE 5 : EAP AIRCRAFT COCKPIT

Pilot Integration and the Implications on the Design of Advanced Cockpits

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Summary

A totally enclosed cockpit may quickly become the driving factor for the next generation of tactical fighter aircraft and will deny access to the pilot of essential outside world cues. Furthermore, the number of sensory systems carried aboard the aircraft is increasing, with the threat of unacceptable pilot workload. Pilot and aircraft reaction times may be a decisive factor in any conflict situation in the future, so the pilot must have a greater situation awareness than ever before.

The future cockpit designer must have a greater appreciation and awareness of the human factors related issues, and in addition tailor system performance to match human performance limitations.

This paper assesses the cockpit situation and examines how the pilot can be successfully integrated with newly emerging technologies to overcome the problems introduced by a closed cockpit philosophy and increased workload. It concludes with an insight into one possible cockpit solution.

1. INTRODUCTION

Today's conventional cockpit designs do not provide an optimum man-machine interface for the pilot, due mainly to physical constraints in the positioning of displays and controls in the cockpit. Recent advances in technology have resulted in electro-mechanical instrumentation being replaced by computer generated graphic displays, either mimicing conventional analogue instrumentation or presenting highly processed information. The head-up display is still considered to be the primary display surface, which can provide an image over a 40 degree x 30 degree field of view. Other cockpit displays are typically high resolution, colour, cathode ray tubes. These colour displays are mounted in a head down situation so as not to compromise out of the cockpit views, whilst providing some measure of protection against high ambient lighting effects. The positioning of these displays is generally governed by physical installation constraints. The illustration given in Figure 1 shows the advanced cockpit that has been used with the Avionic Systems Demonstrator Rig (ASDR) at British Aerospace, Brough. Compromises had to be made during the design of the cockpit such as the positioning of the centre head level display. Installation of the head up display at the correct design eye position forced the two standby instruments to be sited below the up-front control panel of the head up display. Immediately below these instruments is the head level display. In essence the positioning of these devices was governed by the depth of the standby instruments which had a behind panel depth of some 200 millimetres. These instruments now have a behind panel depth of about 20 millimetres. This now allows them to be fitted in place of the up-front control panel, thereby raising the head level display to it's correct position.

The future fighter pilot will be expected to wear bulky protective clothing to enable him to withstand hostile battle field threats. The resulting combination of very restrictive head gear and gloves means that the pilot is being denied access to his machine. (Refer to Figure 2) A fully suited pilot can hardly reach more than 25 percent of the available control panel area. Add to this the effects of 'g', (perhaps caused by even a gentle manoeuvre) then the pilot can be in serious trouble. About fifteen years ago the advent of micro-processor based systems was seen as a means of reducing pilot workload through priority and scheduling of pilot tasks. Unfortunately, pilot workload has increased due to a more capable enemy. The aggressor's smart weapons will demand even faster reaction times from the pilot and his defence systems. Any time advantage, that the pilot can gain over his aggressor will be a decisive factor in any hostile engagement. Aiming weapons through a relatively narrow field of view head up display will require the pilot to position his aircraft so that the target is within the field of view of the head up display. A definite time advantage could be gained if the pilot could designate the target by his line of sight which effectively operates over a wider field of view. This will mean that multiple target attacks could be performed more effectively.

Any reduction in pilot mobility will tend to decrease his time advantage, and so make him more reliant on his on-board sensors and processing systems. Today's technology has reached the point where significant computational power is available. The over-riding weakness lies with on board sensors and their level of integration with the avionics system, and the pilot's ability to assimilate the vast amount of available data. The future cockpit designer needs to consider information transfer more carefully than ever before, because this area will be the 'bottle-neck' between the man and his systems. Understanding human cognitive processing will feature highly throughout any future cockpit design process. Designers will have to interface the pilot very closely with his systems to ensure an effective solution. Whatever approach is taken it will be necessary to consider the effectiveness of the interface under failure conditions, in other words, 'How will the system operate in the event of system failures, and will the pilot be able to continue his tasks ?' Unless we are prepared to accept fully automated attack and defence systems then the cockpit will be a critical source of mission success. The pilot will remain accountable for the actions of the aircraft. One of the main requirements of the future military cockpit is the need to communicate a three dimensional spherical awareness to the pilot, such that his overall situation awareness is not compromised. Existing cockpit displays are constrained to a two dimensional presentation. A major difficulty facing the designers of the next generation of advanced cockpits is the lack of understanding or even definition of situation awareness. Clearly it is important to measure how well the future cockpit design communicates overall situation awareness to the pilot. Without this metric designers will not be able to assess the benefits of integrating the pilot in a particular way.

1.1 Current Visual Capability

The normal human visual field is shown in Figure 3 which shows the position of binocular vision. The standard MK4 flying helmet and oxygen mask reduce the visual field to that approximately given in Figure 4. It should be noted that these illustrations are for a static head position. Any attempt to move the head quickly to track a target will result in the helmet lagging behind head position, with a consequential reduction in the visual field. The standard issue Nuclear, Biological and Chemical (NBC) respirator further compounds this problem because it allows the head to move more freely within the helmet. Under high 'g' levels the pilot will be unable to move his head. Therefore, any compensatory movement of the head to get a good visual field will be impossible. It is well known that the pilot's performance is severely impaired with a reduced peripheral vision. Low level high speed flying can put the pilot and aircraft at risk. Even the wide field of view head up display presenting a field of view of 40 degrees in azimuth and 30 degrees in elevation does very little for look into turn. Although the geometry of the aircraft has an impact on the pilot's visual capability it seems that the pilot's protective clothing may be the limiting factor. Many pilots have been overheard saying "In combat conditions I shall wear my old MK1 leather flying helmet." The lesson to be learnt here is that pilots are crying out for an increased visual capability. The pilot's dominant sensing system is his sight. Therefore, in any future cockpit design we must take a look at new technologies that will improve the visual field. The closed cockpit essentially closes down the outside world view, and the pertinent point here, is the visual field capability of the sensors used to convey the outside world scene to the pilot. It might be tempting to present a monocular scene to the pilot, but what will the loss of depth perception do to his overall flying and weapon aiming capability? The problem becomes particularly acute when trying to land a VSTOL aircraft where all round vision and depth perception becomes particularly important. If binocular vision is required then what angular separation and binocular disparity is required at the stereo sensor unit?

1.2 Dual Interface Crisis

The closed cockpit will cause sensory deprivation to the pilot. Whilst this is a serious problem another equally serious problem is due to the pilot being deprived of movement. This immobility or physical restraint is caused by restrictive clothing and high 'g' levels which makes manual tasks such as switch selection very difficult. Therefore, the cockpit designer is faced with a dual interface crisis:- the visual and control interfaces.

The remainder of this paper describes a route through this 'Dual Interface Crisis'. It will provide the future cockpit designer with an answer to his interface problem.

However, the designer should take particular care with semi and fully automated systems to ensure they are matched to the capability of the human operator.

1.3 Pilot Interaction with Automated Systems

Automated routine pilot functions such as automatic switch checking (during the start up of an aircraft), and auto-pilot functions, could be described as essentially low-bandwidth, and generally do not effect the mission survivability of the aircraft.

Other automated functions such as threat and scenario processing are used to determine attack profiles and egress routes. These are the high bandwidth systems since the pilot would not be able to mentally process the large amount of data, and the mission survivability of the aircraft will most certainly depend on a continual and rapid assessment of the tactical scene. It is these latter systems where pilot interaction is important. There is little point in providing an automated system with fast update rate if the pilot response time, due to data assimilation, is very low. Even though the resulting display data has been highly processed it is important to communicate the true situation awareness as rapidly as possible, particularly if the pilot has to react to the situation by pressing the trigger to give the final release consent to launch his weapons. The author has seen examples of tactical displays where two display surfaces must be used to communicate situation awareness to the pilot. This is an example where the man-machine interface becomes the limiting factor because the tactical situation displays present the battle scene as a series of discrete event points. As time proceeds these event points are spatially updated in order to communicate an overall situation awareness. Even a moment's distraction will require a significant amount of time to assimilate the data again. It 's important therefore, to present the information in an intuitive manner that requires very little time to continually re-assess the scene. An example will illustrate the concept. The display format presented in Figure 5 shows that our aircraft is under threat from two hostile aircraft, the position and directions of which are shown as symbols A and B. The straight vector emanating from each target serves to indicate both direction and relative velocity of the target. In order to take on the two targets it is necessary for the pilot to determine which target presents the greatest threat and destroy it before the other one. It is presumed a tactical decision aid is providing some form of automatic threat assessment, but the pilot still has to assimilate the display. The pilot will have only seconds in which to react to these changing threat conditions. Therefore, careful thought must be given to the way that data is presented to the pilot. One possible display technique is given in Figure 6 which shows the same three hostiles, but this time overlayed with a probability of kill contour map. The pilot is able to quickly determine from which area the greatest threat occurs and where positions of advantage can be found. In a similar way it is also possible to display probability of survival as shown in Figure 7. (The reader should note that for purposes of reproduction, the display is shown in monochrome, whilst for the cockpit display, full colour will be used.) Nevertheless, it is still necessary to measure the level of situation awareness that these displays communicate over and above the earlier presentations. Even though we do not yet have defined measures of situation awareness, perhaps pilot reaction times are one of the key parameters that could be used as a first order assessment.

2. PILOT CONTROL

2.1 Intuitive Direct Voice Input

Much has been written on the subject of voice control. Indeed, there are many excellent systems available off the shelf which can achieve a high recognition rate. Application of these systems to the military cockpit has been slow and generally confined to research vehicles. The restrained pilot will have to rely more on the spoken command in order to interact with his systems. Although there are questions relating to the use of voice command in high 'g' levels and high stress situations, it is necessary to consider whether or not the pilot could use the system to his advantage in less arduous situations.

Most modern aircraft employ some form of centralised briefing system which allows the pilot to enter the aircraft with a small portable data store containing route information, tactical data and weapon configurations. This data store is used to brief all the necessary avionic systems and relieve the pilot of a lengthy and tedious numerical input task. Furthermore, each navigation point may require as many as ten or more separate data values representing latitude, longitude, overfly height, etc. If the aircraft is operating from a dispersed or make-shift airfield without access to a briefing ground station, then the pilot is faced with a daunting task. Voice control would seem to be a reasonable solution to deal with this unwieldy mass of data.

Any reduction in control panel space for whatever reason will require an alternative means of inputting the same data.

Early efforts with voice input have been directed towards high recognition rates and large vocabularies. A somewhat contradictory requirement in a noisy aircraft environment. A spin-off from data bus orientated aircraft is the large data base that is potentially available on board the aircraft and which could be used to determine the context of the aircraft. This context will typically describe aircraft state, flight phase etc., all of which could be used as a filter or mask for a speech recogniser's vocabulary. Contextual decoding in the speech recogniser would reduce the size of the vocabulary search, and increase recognition accuracy. The total on-board vocabulary will be very large and could be broken down into sub-sets according to context requirements. Studies suggest that this contextual decoding could be performed with very little computational overhead, providing the whole aircraft system is driven by a series of Finite State Processsors. (Finite State Processing is dealt with in Section 4.2.)

A technique requiring further research is 'pre-emptive prompting'. Here the pilot would be prompted with key words appearing on the read-out line on his display. These key words would be those most appropriate for the action currently being formated. If it is not possible to devise a free and flexible syntax structure, then 'pre-emptive prompting' may guide the pilot through the correct sequence. It still has to be determined whether or not only command displays are to be permitted. Nevertheless, in the test equipment world, demonstrations of 'pre-emptive prompting' have proved to be a very effective method of controlling a complex system. Clearly, the technique could be applied to both direct voice input and menu selections on a display head.

2.2 Eye Switching or Control

Employing the eye as a switching mechanism has been proposed for some time as a biocybernetic control approach that may be used to reduce pilot workload. The pilot would move his line of sight to a control surface in order to select weapons, display modes, etc. Eye control would eliminate the need for selective manual responses. Eye tracking and oculometer systems have been in use for a number of years to assist in basic workload experiments and in research connected with producing television advertisments. Early eye tracking systems were bulky and required a fixed head position, but more recently systems have become smaller, and therefore do not require a fixed head position, making them more suitable for consideration as a cockpit system. Research reported by Calhorn 1986 has shown that eye switching is a feasible alternative to manual switching, and would be faster than a voice activated system. When the pilot is 'head-out' of the cockpit then eye switching would allow certain essential control tasks to be completed, without the pilot having to direct his attention inside the cockpit.

Eye tracking systems are concerned with saccadic eye movements. These are the rapid conjugate movements by which we change fixation from one point to another voluntarily, and include the jump and rest fixation movements observed in scanning a visual scene. They are characterised by very high initial accelerations and a final deceleration (40,000 degrees/sec/sec). An excellent survey of eye movement recording methods is given by Young 1975 and will not be repeated here.

To make use of eye tracking systems in the cockpit it will be necessary to be able to track eye positions of different sized pilots over a wide variation of illumination levels. Obviously if the closed cockpit does become a requirement, then ambient lighting levels could be carefully controlled. The more interesting challenge comes from the engineering task of integrating the eye tracker optics with the helmet mounted display. Both systems will have to share the same optical path in the confines of a standard flying helmet but must not unduly increase the weight of the helmet.

Urgent research is required in this area to understand the basic human factor's issues. An equally important activity to be addressed is the integration of an eye point of regard sensor with helmet mounted displays. If we assume that this can be achieved, then we must consider how to use eye position sensing in the cockpit.

2.3 Logical - Physical Control Input

Dedicated controls arranged on separate control panels, (performing functions such as communication management, radar moding, etc.) have made the existing cockpit fairly rigid with regard to input protocol. Experimental aircraft, with speech recognisers, still need to have dedicated back-up controls in the event of speech recogniser failure.

In the cockpit of the future, where there may be a multiplicity of sources of control information such as voice command, eye fixation, and tactile and aircraft system state, we need some means of managing this interface. It would obviously be possible to connect these signals together in parallel, but that could *lead to contention* in the event of failure or where pilot must over-ride any automatic selection. Fortunately, if we look to the computing fraternity there is a ready made solution that has been designed to manage multiple channel access to a finite set of resources. This is the mapping of logical or pseudo devices onto physical devices. The operating system assigns pseudo devices to the user and connects them to physical devices. The user never needs to worry about the physical devices, indeed the physical devices may change according to resource management. Access priorities can be established easily and avoid conflict. It is a simple matter to apply this philosophy to the cockpit by assigning the various input systems as pseudo channels, and allowing a cockpit operating system to effectively manage the resources. The operating system could disable inputs in the event of failure, and allow backup channels to gain authority. It would seem appropriate to address contextual decoding as a means of filtering on the control input. (Refer to Figure 8.) The author believes that the Finite State Processing technique as described in Section 4.2 could be used to easily implement the cockpit operating system. The concept of pilot intent engine has been indicated by Furness, 1986, and it would seem possible to run this system in parallel with the cockpit operating system, and compare pilot action with predicted action. This would provide some measure of pilot cross monitoring with perhaps some form of visual feedback in the event of disagreement.

2.4 Flight Control Inceptors

Irrespective of the type of technology employed for the cockpit there will always be a need for the pilot to manually fly the aircraft. Active control technology, has removed the direct connection between the pilot and the aircraft's control surfaces, to ensure that the aircraft remains within the safe part of the flight envelope whilst auto-pilot functions reduce the amount of time the pilot spends correcting his course.

Thrust demand can similarly be controlled, and is particularly important for vertical or short take off aircraft. Even though these automated systems relieve the pilot from certain tasks, he must still be able to input demands into the system and be able to achieve control in the event of failure. The VSTOL aircraft presents a fairly difficult task for the pilot to fly in a semi-automatic or manual mode. The pilot has to manipulate thrust and nozzle control to maintain the fine balance in the transition stage between vertical take off and conventional flight. Combat manoeuvrers in the Harrier using nozzle angle requires manipulation of both thrust and nozzle levers in conjunction with pitch or roll demands on the stick. The net control interface is rather awkward and difficult to maintain. An integrated left-hand inceptor with an advanced flight control system which has integrated nozzle angle and thrust demand onto one assembly will be required. This arrangement *will result in a* 'natural' control interface with ample room for the inclusion of several HOTAS controls to compliment those on the stick. Figure 9 illustrates the integrated left hand inceptor that has been used in the ASDR Advanced Cockpit.

Flight control inceptor transducers are particularly vulnerable to the effects of electro-magnetic pulse (EMP) and lightning strikes. Transducers used to sense either rotary or linear position currently employ electronic means to sense position. Complete screening against EMP can be achieved, but the associated wiring remains vulnerable. It is conceivable that the future flight control computer will have pure optical interfaces with the outside world. All the sensitive electronic equipment would be housed in tightly screen enclosures.

2.5 Optical Switches

An optical switch system has been proposed (patents applied for) and makes use of a small bar code or similar code etched onto the moving part of the switch mechanism. As the switch is activated the bar code modulates the light beam that is transmitted over the fibre-optic cable. A remote bar code reader will decipher the signal before informing the appropriate control computer. Error correcting and checksum techniques can be readily applied to the system to improve the integrity of the overall system. A refinement of the system will be the utilisation of an optical bus that would be used to connect the individual switch units together and reduce the amount of interconnecting fibres. A single fibre-optic cable and bar code reader would thus serve a number of switches.

The *resulting switch system* will not be susceptible to electro-magnetic interference whilst being very 'quiet' in operation with no radio frequency emission.

3. PILOT VISUALS

3.1 Helmet Mounted Displays

Conventional head up displays tend to have a practical limit on the total field of view they present. This limit tends to be governed by the size of the combiner or holographic elements used to relay the image into the pilot's eyes. The maximum value is around 40 degrees in azimuth and 30 degrees in elevation. The other disadvantage is that the image is bore-sighted to the aircraft which means that flight information is constrained to only a small part of the total 4π steriadian field of view.

The helmet mounted display presents an image at infinity that is bore-sighted to head line-of-sight. The optical combiner is positioned much closer to the eye than a conventional head up display which results in a very wide field of view. Either monocular or binocular displays can be considered, each ocular, presenting instantaneous fields of view of about 80 degrees in azimuth and 60 degrees in elevation. The combined binocular field of view will be 120 degrees in azimuth by 60 degrees in elevation, *allowing* a 20 degree overlap for true binocular viewing, with the total field of view being limited only by a head movement.

The attraction of a very wide field of view is enormous, but helmet weight must be considered. The standard MK4 flying helmet is just about acceptable under conditions of high 'g' but any increase in weight caused by adding helmet mounted displays is clearly going to be a problem. If we consider helmet mounted miniature colour cathode ray tube (CRT) then we must address the problem of practical display resolution. The display

from the CRT will have to be projected onto a field of view of 80 degrees by 70 degrees which means that a very high resolution will be required from the CRT. Current full colour CRT's fall short of this requirement because of phosphor granularity, spot size and shadow mask spacing. Limiting the colour range to just a few colours will mean that penetron devices could be used which will eliminate the shadow mask.

Other HMD concepts worthy of consideration are those which employ remotely mounted CRT's. The image is relayed to a helmet mounted combiner, via a coherent fibre optic bundle, refer to Figure 10. Apart from reducing helmet weight it is possible to employ a larger CRT, thus increasing the resolution. The larger CRT would certainly be able to produce a brighter display with the added advantage that high voltage supplies would be off the helmet. During an ejection only an optical interface will be required to separate thus avoiding the production of an electrical discharge. Care has to be taken with the design of the helmet if it is to be fitted with a miniature CRT device, collimating lenses and drive electronics, because it would be easy to upset the centre of gravity of the helmet. This would then affect the pilot's head movements under 'g' loadings.

Inspection of standard Nuclear, Biological and Chemical protective clothing, will reveal a problem with the narrow field of view that results from the oxygen respirator assembly (Refer to Figure 2a). A helmet offering an enclosed environment might be one possible solution. The helmet visor could be used as the display combiner and will be made with holographic elements. (Figure 11.)

3.2 Helmet Position Sensors

The concept of the helmet position sensor is straight-forward and several devices have been commercially available for many years. Sensing techniques either employ magnetic field, infra-red beam or ultra-sonics to resolve head position with six degrees of freedom:- azimuth, elevation and roll in orientation and x, y and z in position. Each sensing technique has it's own merits, but the magnetic system tends to be more accurate and less troublesome in operation. The primary role of head position sensors has been for off bore-sight weapon aiming with simple reticle helmet mounted displays. High accuracy and fast update rates were never a requirement for these early systems, and it is unfortunate that these systems never gained their rightful place in the cockpit. This may be attributed to the simple display presentations that were possible with the technology at that time.

In the future, helmet position systems will become the major pilot interface with the avionic system. Electronic hybridisation has led to very small cockpit units adding very little weight to the helmet.

In considering the operational requirements of the helmet position sensor it is necessary to understand how the head position data is being used. If a visually coupled system is proposed then attention will have to be given to the accuracy of the sensed head position and the response time. Any lags in the system will introduce disorientation effects in attitude presentations.

4. DESIGN METHODOLOGY AND TOOLS

The next generation of cockpit design can be divided into two main phases with respect to the design methodology and the required tools. Firstly, we have the methodology and tools to enable the designer to realise his ideas and make reasonable estimates to the likely efficiency of the man-machine interface. Secondly, we have the manner in which the man integrates with his systems. With several ways of interacting with his systems it will be necessary to devise an interface protocol. It is also tempting to close the loop between the man and his systems by monitoring certain physiological conditions in order to determine, pilot state of consciousness and measure of workload. Having specified a series of measures we need to consider how we can make use of this data in order to control the avionic systems. For example, 'g' induced loss of consciousness monitoring or perhaps initiation of load shedding during workload saturation.

4.1 Virtual Manikin Design Tool

Ergonomic based design tools such as Micro-Saint and Sammy are available. These allow simulations or models of systems to be built and analysed. The tools allow a certain degree of understanding to be achieved regarding physical man but tend to be cumbersome to use.

Traditional cockpit layout tends to rely upon the manipulation of a two dimensional plastic manikin over a suitably scaled drawing of the cockpit. The manikin has been designed so that it can represent different sized pilots and employs suitable linkages to restrict limb movement to that of a human being. These manikins are used to visualise reach distances etc., before the drawing is committed to the model shop for fabrication of a wooden space model. However, the majority of other aircraft design work is undertaken by computers with particular emphasis on computer aided design via graphic work stations. Attempts have been made to represent or model human dynamics in a computer, but at best these systems present simple manikin structures and make limited use of graphics. British Aerospace are developing a fully articulating three dimensional representation of a manikin. It will be possible to combine this manikin with a three dimensional representation of the cockpit structure. The advantages of this system are enormous, the user can quickly change the size of the manikin and determine whether or not his design will work for all pilots and positions. It is envisaged that the output from standard models, such as Micro-Saint or Sammy will be input into the virtual manikin package in the future. One significant advantage with the package is the ability to re-position the designer's view-point from the side of the manikin to inside the manikin's head and visualise the cockpit as would be seen by the pilot. The model will eventually be refined to represent the field of view restriction imposed by helmet and night vision goggles, etc. The user will be able to articulate the manikin's head and observe the effect on the pilot's view of the cockpit. This virtual manikin is seen as an important step in cockpit layout techniques. By instrumenting a pilot it will be possible to record limb positions, and replay this through the virtual manikin in slow motion to analyse in detail the man-machine interface. The whole package could be hosted on a small desk-top computer for wide-spread use. By simple refinements it will be possible to develop the program into a virtual cockpit design tool.

4.2 Finite State Processing

The finite state processor (FSP) is a mechanism for defining system state changes that result from externally or internally generated events. These events could be pilot inputs or outputs from various avionic sub-systems. The technique is potentially the most powerful method of specifying and implementing complex system interaction. These techniques have been used extensively on the Ministry of Defence Avionic Systems Demonstrator Rig with significant savings in the production of software. A spin-off from the technique is an unambiguous, yet highly visible system specification that can be used by the system's integrator or equipment sub-contractor.

The FSP is based on a series of finite state tables that describe a system via a series of cells, which define a sequence of actions to a given input signal according to system state. A complete system may be represented by a large finite state table, or a number of smaller finite state tables some generating signals for other tables.

The finite state table comprises a series of cells which define a series of actions. The various states are listed in rows and the signals are listed in columns. Each cell representing a valid state contains two entries. In the upper left corner is the state that will be entered when the given signal is generated, and in the lower right hand corner is a pointer to the action requiring to be performed prior to the state change. For cases where a state change needs to occur without a corresponding action, then the lower right part of the cell remains blank. If the system is in a state where a particular signal may occur but the system must not act upon it, then both halves of the cell must remain blank but separated by a diagonal line Undefined states remain blank but separated by a diagonal line. Undefined states remain blank, and should never be entered. The best way of explaining the technique is by way of an example. Figure 12 shows a typical communication system control panel. The finite state table used in the communication sub-system is shown in Figures 13 and 14. In the example the FSP state 'SYSTEM OFF' represents the powered down state of the system. Whilst in this state the only valid signal is 'POWER APPLIED' which initiates a change of state to POWERED UP and causes Action 17 to be performed. Action 17 in this case initiates a procedure which checks whether the active transmitter is on HF or on V/UHF. State 2 is then entered. If the active transmitter is on HF then Action 1 is performed and then State 3 is entered. Action 1 causes a state response to be sent to the avionics bus controller. State 3 is the selection of the HF T/R active but not transmitting. If the Press To Talk (PTT) switch is pressed then Action 3 is performed which causes the transmitter to start transmitting before moving to State 8.

The operation of the FSP relies on discrete event signals initiating state changes within the FSP table. In some cases it may be necessary to delay or inhibit the generation of signals that normally act directly on the FSP while the system is in certain states. This is achieved by means of the procedure or process.

Procedure: A procedure can be defined as a series of instructions that are executed whenever the procedure is called. Procedures are under normal circumstances, self terminating, and can only be called from within an action, another procedure or a process.

Process: A process can be defined as a procedure which upon initiation from within an action will automatically execute at a defined rate until it is halted, either from within a subsequent action or by the process itself.

Although the concept of the FSP seems fairly straight-forward the real benefits come from the fact that a series of software tools have been developed to take the FSPs directly into high level code. The engineer can design the FSPs using a graphics work station during an interactive session, and generate the high level code via an automatic program generator. Modifications or additions can be made quite simply. The whole process being essentially self documenting. Other tools are being developed that will allow complete standalone testing of the newly created FSP prior to generating the code.

By representing an avionic system with FSPs we can build a completely deterministic representation of all the states that the system can enter. The author has applied a variation of this technique to specify and control the display moding of a single seat fighter aircraft, Kalawsky 1983.

5. VIRTUAL CREW WORK STATIONS

Cockpit designs, as we known them today, will have to change radically if we are to retain an advantage over an aggressor. We cannot be too sure whether the battle will be fought with stand-off missiles, such that the pilot never sees the other aircraft, or, whether the pilot will be engaged in air to air combat. But we can be sure that the battle field will be very hostile and fast reaction times will have a marked effect on the outcome of the battle.

Installation constraints will continue to impose restrictions on the man-machine interface. Therefore, any solution which overcomes these limitations will increase mission success The virtual cockpit which will now be described is such a solution, and could be achieved with today's technology.

A virtual crew work station is a visual presentation of a control panel, and perhaps an outside world scene, that is projected for the operator. The display is generated by a computer graphic machine and could be projected onto a reflective surface, or presented to the eye via an optical combiner and a series of lenses. The system provides a visual yet virtual representation of a real control area.

Helmet mounted displays and sighting systems to date are only target designation systems to allow off-bore sight weapon aiming, with perhaps slaving of an off-bore slight sensor. The initial role of the helmet mounted display was to generate head stabilised weapon aiming cues perhaps supported by additional attack symbology.

The concept of a visually coupled system has been published as early as 1980. The visually coupled system is a display system that is integrated with a head position sensor so that as head position is varied a new helmet mounted display image is computed, thus allowing the possibility of space stabilised imagery to be presented to the pilot.

Realisation of the virtual crew work station has to date been hindered by the level of technology required to support the system. Only recently has the technology been available to sense head position sufficiently accurately, in conjunction with advanced real-time graphic systems, to produce the required presentations. For *airborne applications, size and weight are of particular importance.*

The concept of a virtual work station is extremely straight-forward. The operator is presented with a computer generated representation of his control area, such as a control panel complete with switches and displays. As the operator moves his head the display will remain space stabilised so that the control panel will move out of the operator's field of view as he turns his head. Clearly, this assumes that head position is used to compute the new display view-point. If a helmet mounted display is utilised, then it is conceivable that a full 360 degree Total Field of View (TFOV) could be presented. The Instantaneous Field of View (IFOV) would be limited to that of normal human vision. The operator could move his IFOV port hole around the TFOV, and head position would be used to compute the required display presentation. In a military cockpit this offers the possibility of being able to 'see through' the floor or other cockpit structures, providing that suitable sensors have been incorporated.

The visually coupled system requires *head pointing data with six degrees of freedom:- azimuth,* elevation and roll in orientation and x, y and z in position. The head pointing data is then used by the graphic system to compute a correctly orientated virtual display.

It is necessary to present data as:-

a) head stabilised :- head aiming

b) cockpit stabilised :- virtual control panels

c) ground stabilised :- target locations and way- points (ground referenced objects)

d) space stabilised :- flight information

5.1 Virtual World Interaction

The operator ,or pilot, will require some means of interacting with his virtual world. Obvious solutions include - direct voice input, head position sensing, fixed eye sight. Eye fixation could be used to advantage, but this implies that an unobtrusive eye tracker is used. Under high 'g' conditions as might be experienced in a fighter aircraft, eye tracking systems may become the most effective means of interacting with the aircraft system.

It is likely that some, if not all, of the above interaction mechanisms will be used in the next generation cockpits. One question raised at this point is - 'Which selection method is best and could it be better achieved via a different method at a different point in the task?' Until more human factor's research is undertaken we can only guess at the answer, but we can be fairly sure that the human operator may be more effective if numerous access channels are open to serve the task. From *a system view point* how does the designer cope with all the possible access channels? For instance, the pilot aids aboard the aircraft may require to autonomously select a particular function. The pilot may need to over-ride one of these events but *how will this be achieved? Ideally, whichever approach* is decided upon it is essential that some form of selection validation is performed, perhaps by some element of context decoding.

A requirement for a cockpit operating system or Executive Function is emerging to provide a flexible and yet intuitive interface to the aircraft system. British Aerospace engineers have developed a technique on the Avionics System Demonstrator Rig based on a finite state. The approach has been so successful it has been applied to the specification of all sub-systems in a form that can be unambigously used by the individual sub-system manufacturers to the systems integrator. Software tools have been specifically developed which will take engineering descriptions of system operation into executable code. If employed these automatic program generation techniques could significantly reduce the cost and man years of software effort for the next generation aircraft. A further advantage lies with the addition of new features or modifications in the future. Here it is a simple matter to incorporate modifications at a high level, and the low level code produced automatically. The whole process is essentially self documenting, thereby reducing costs further. Code can be produced for any machine with a suitable target generator module. Additional software tools are being developed allowing the complete system to be tested and validated prior to release. Future refinements could include the ability to dynamically alter the contents of the finite state tables giving the system a learning capability. The concept of a knowledge base with a learning capability could be an important feature for future avionic systems making the overall avionic system more fault tolerant.

6. ADVANCED COCKPIT CONCEPT

British Aerospace are involved in developing virtual work stations that can be applied to cockpits and any work station requiring human interaction. The work station will be based on a modular crew station employing panoramic visual and auditory displays. The major concept revolves around a virtual crew station so that information from aircraft sensors, navigation, communication and weapon systems is organised and presented to the pilot in three dimensional space. The virtual crew station is perhaps the most exciting concept to be applied to cockpit design since the advent of the micro-processor.

Boff, 1986 points out that the design of an aircraft system involves balancing trade-offs among many sub-system priorities to achieve a required functionality within material, cost and timescale constraints. The interdependence among the large number of variables that contribute to the overall design make it difficult to predict the influence of any one variable. The most popular slogan used at present is 'situation awareness' which does seem to be the most appropriate metric to use to determine system effectiveness from a man-machine interface view-point. Unfortunately, no single or series of measurements can be defined that precisely define 'situation awareness'. It is known that situation awareness has a bearing on pilot reaction time and perhaps this could be used. However, it is likely that other parameters

will have to be measured to provide a precise measure of situation awareness.

A basic system architecture is shown in Figure 15.

7. CONCLUDING REMARKS

This paper has alluded to the dilemma facing cockpit designers of future aircraft. An enclosed cockpit along with protective clothing will limit the pilots ability to interact with his systems and maintain an awareness of the outside world. Recent advances in technology have been discussed with a view to identifying candidate technologies that could solve many of the cockpit designers problems. There is no doubt that the next generation of cockpit will have to be based on a considerable amount of human factors research. One of the most critical areas of research is the definition and measurement of situation awareness so that it can be used in the design process. A series of new design tools will also be required to deal with the integration of cockpit systems, especially where more automation is demanded.

The techniques of Finite State Processing have been described with particular reference to an existing system. The applicability to contextual decoding has been described but one potential application for future avionics is the concept of a FSP system that can learn. British Aerospace engineers have conceived the idea of a large FSP or series of interconnecting FSPs that can update their own cells to provide a self teaching capability. Little can be said at this stage except to say that the techniques and tools developed to date lend themselves to this application. Application to fault tolerant or self repairing systems is obvious.

The most significant concept to emerge in the cockpit world is the virtual work station that can be software re-configured. Since the virtual crew work station is based on a visually coupled system the cockpit designer is no longer faced with an inflexible physical structure. The designer will be able to maximise the pilot's visual capability in a way that has never been possible before. The pilot will be able to interact intuitively with his systems in a natural manner.

Although this paper has dealt with a single crew station the virtual work station could be applied to any work station in the future where a human operator has to interact with a machine. The visually coupled virtual work station will completely revolutionise the man machine interface as we know it today.

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9. ACKOWLEDGEMENTS

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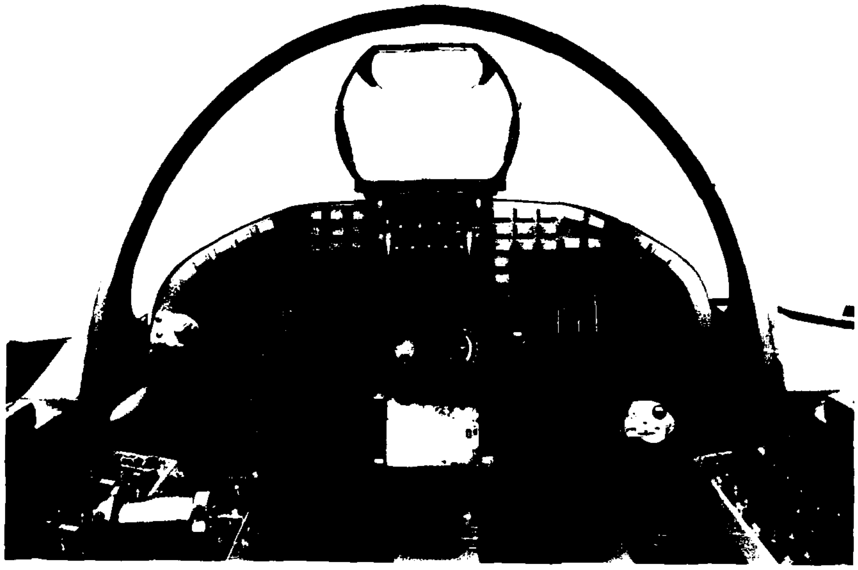
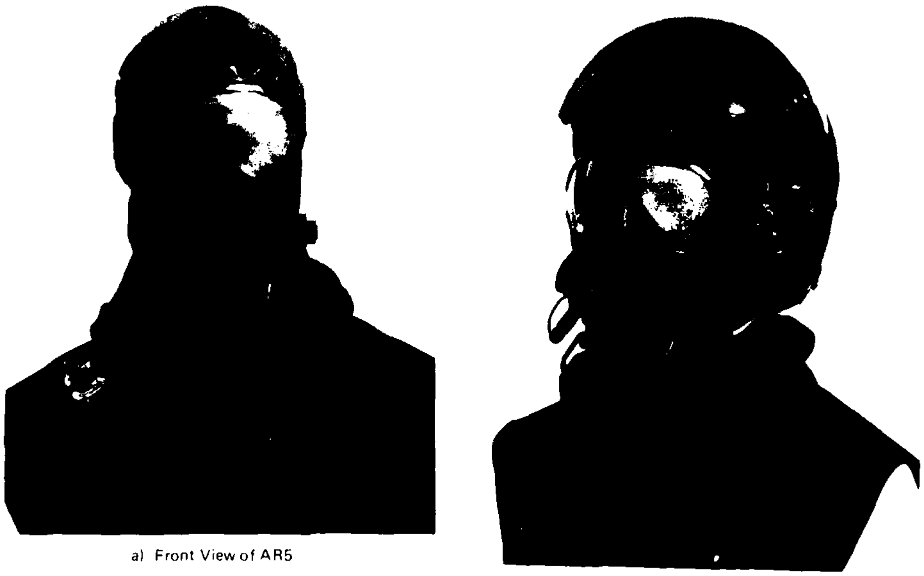


Figure 1 Mk 5 Advanced Cockpit



a) Front View of AR5

b) Side View of Protective Helmet worn over AR5

Figure 2 Aircrew Protective Head Gear (NBC Hook and Mk 4 Helmet)

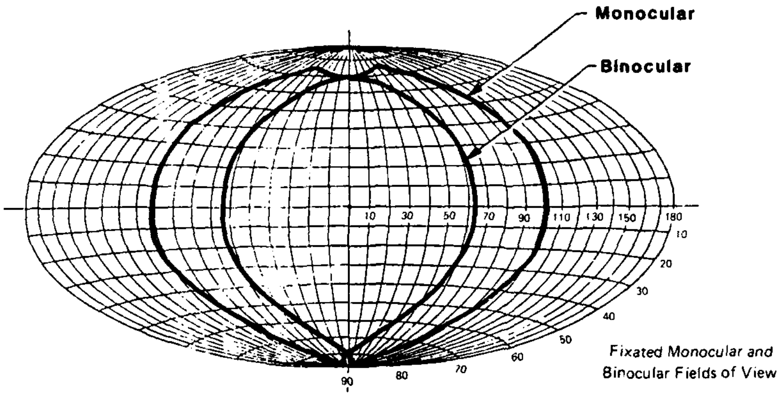


Figure 3 Normal Human Visual Field

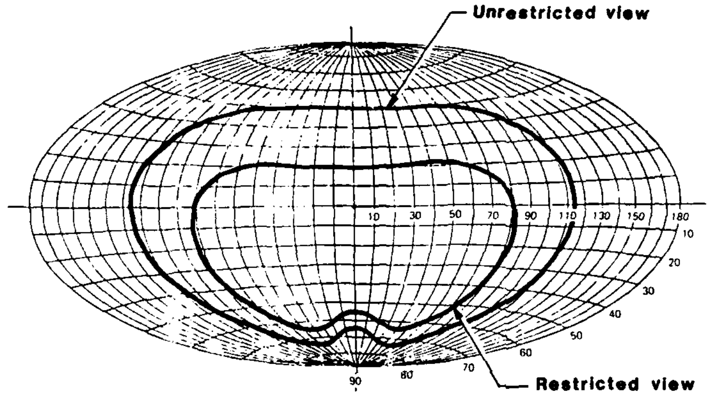


Figure 4 Typical Obscuration caused by Helmet/Mask

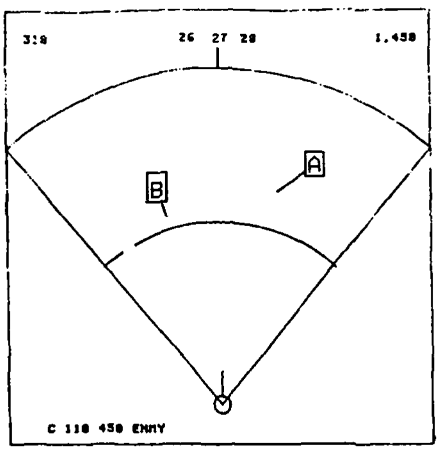


Figure 5 Threat Assessment Display
Poor Situation Assessment

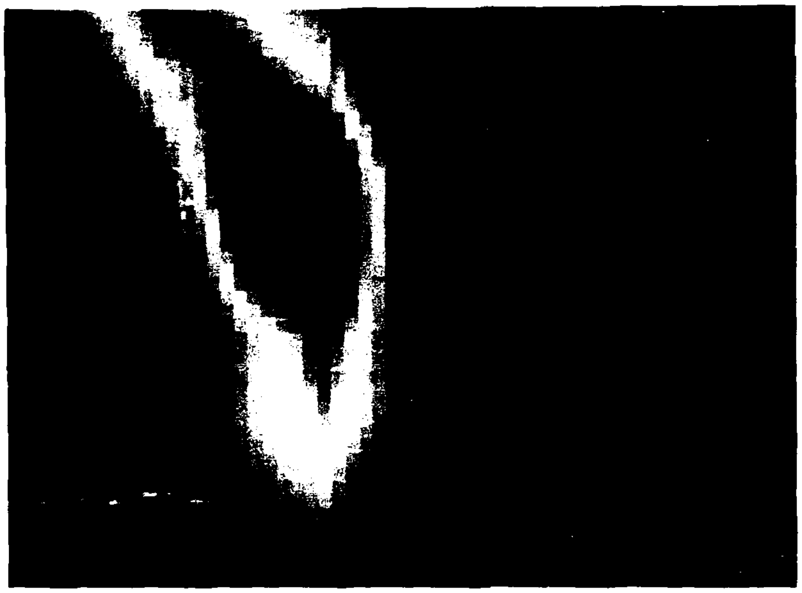


Figure 6 **Threat Assessment – Probability of Kill**
Good Situation Assessment

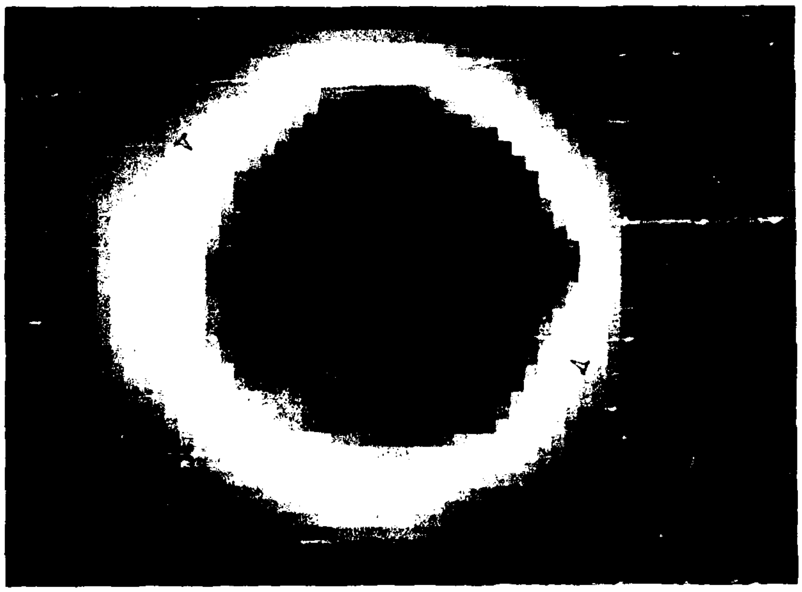


Figure 7 **Threat Assessment – Probability of Survival**
Good Situation Assessment

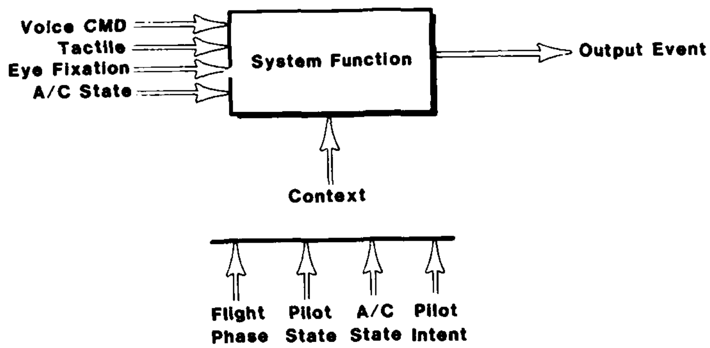


Figure 8 Context Decoding

Figure 9 Integrated Left Hand Inceptor

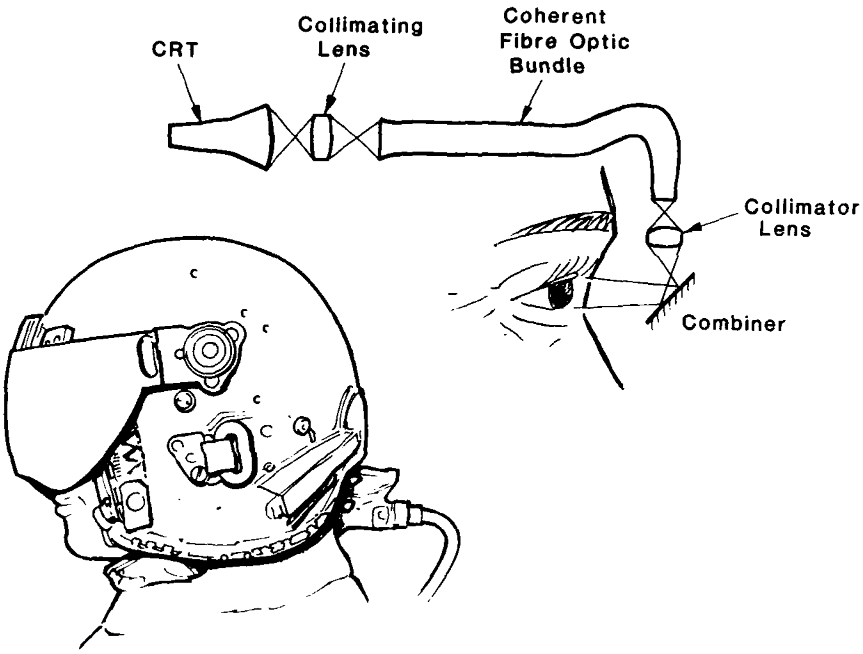


Figure 10 Remote Optics HMD

Figure 11 Holographic Helmet System

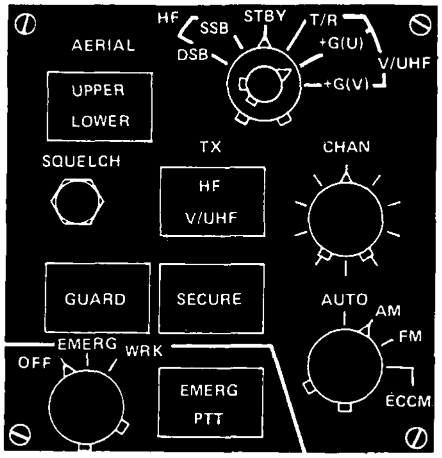


Figure 12 Communication System Control Panel

CTLPANEL
VER. 2
15-SEP-1987
08:49:55
FSP NO. 5

		1 POWER APPLIED	2 ACTIVE TX ON HF	3 ACTIVE TX ON V/UHF	4 HF T/R TX'ING	5 HF T/R NOT TX'ING	6 V/UHF T/R TX'ING	7 V/UHF T/R NOT TX'ING	8 PTT ON	9 PTT OFF	10 AERIAL UPPER	11 AERIAL LOWER	12 SQUELCH IN	13 SQUELCH OUT	14 DISABLE NORMAL OP FSP
1	SYSTEM OFF	2/17													
2	COMMS IN NORMAL OP		3/1	5/2							/13	/14	/15	/16	1/
3	HF T/R ACTIVE NOT TX'ING			5/2				/	8/3	/4	/13	/14	/15	/16	1/
4	HF T/R ACTIVE TX'ING			10/3				/		7/6	/13	/14	/15	/16	1/
5	V/UHF T/R ACTIVE NOT TX'I		3/1			/			10/7	/4	/13	/14	/15	/16	1/
6	V/UHF T/R ACTIVE TX'ING		8/6			/				9/5	/13	/14	/15	/16	1/
7	HF STOP TX'ING REQUEST					3/4					/13	/14	/15	/16	1/
8	HF START TX'ING REQUEST				4/10	3/11		/			/13	/14	/15	/16	1/
9	V/UHF STOP TX'ING REQUEST							5/9			/13	/14	/15	/16	1/
10	V/UHF START TX'ING REQUES						6/10	5/11			/13	/14	/15	/16	1/

Figure 13 FSP for Communication System (simplified)

DESCRIPTION OF STATES

SYSTEM OFF : This state is entered when the Comms system is no longer operational

SYSTEM ON : This is a transient state which is accessed while other signals are being evaluated

HF T/R ACTIVE NOT TX'ING : This state is entered when the HF T/R is nominated active on transmit, but is not transmitting

HF T/R ACTIVE TX'ING : This state is entered when the HF T/R is nominated active on transmit, but is required to transmit

V/UHF T/R ACTIVE NOT TX'ING : This state is entered when the V/UHF T/R is nominated active on transmit and is not transmitting

V/UHF T/R ACTIVE TX'ING : This state os entered when the V/UHF T/R is nominate active on transmit and is required to transmit

HF STOP TX'ING REQUEST : This is pseudo transitory state which is entered when HF transmission is no longer required

HF START TX'ING REQUEST : This is pseudo transitory state which is entered when HF transmission is required

V/UHF STOP TX'ING REQUEST : This is a pseudo transitory state which is entered when V/UHF transmission is no longer required

V/UHF START TX'ING REQUEST : This is pseudo transitory state which is entered when V/UHF transmission is required

DESCRIPTION OF SIGNALS

POWER APPLIED : This signal is internally generated when Comms has power applied

ACTIVE TX ON HF : This signal is a command from the avionics bus controller / executive for the HF transmitter to become active and to transmit when the PTT is pressed.

ACTIVE TX ON V/UHF : This signal is a command from the avionics bus controller / executive for the V/UHF transmitter to become active and to transmit when the PTT is pressed

HF T/R TX'ING : This signal is internally generated when the HF T/R is transmitting

HF T/R NOT TX'ING : This signal is internally generated when the HF T/R is not transmitting

V/UHF T/R TX'ING : This signal is internally generated when the V/UHF T/R is transmitting

V/HF T/R NOT TX'ING : This signal is internally generated when the HF T/R is not transmitting

PTT ON : This is an avionics bus controller / executive command for the active T/R to start transmitting

PTT OFF : This is an avionics bus controller / executive command for the active T/R to cease transmission

AERIAL UPPER : This is an avionics bus controller / executive Command for the upper aerial to be selected

SQUELCH IN : This is an avionics bus controller / executive Command for the squelch on the V/UHF T/R to be enabled

SQUELCH OUT : This is an avionics bus controller / executive Command for the squelch on the V/UHF T/R to be disabled

DISABLE NORMAL OP FSP : This signal is internally generated when normal operation of the Comms is no longer required or available

DEFINITION OF ACTIONS

Action [1] 1. Send State response 'Transmitter active on HF'

Action [2] 1. Send State response 'Transmitter active on V/UHF'

Action [3] 1. Generate the internal signal 'HF T/R START TX'ING' for the HF T/R FSP

Action [4] 1. Send SWR 'Neither T/R transmitting'

Action [5] 1. Generate the internal signal 'HF T/R STOP TX'ING' for the HF T/R FSP
2. Generate the internal signal 'V/UHF T/R START TX'ING' for the V/UHF T/R FSP
3. Format state response 'Transmitter active on V/UHF'

Action [6] 1. Generate the internal signal 'HF T/R STOP TX'ING' for the HF T/R FSP

Action [7] 1. Generate the internal signal 'V/UHF T/R START TX'ING' for the V/UHF T/R FSP

Action [8] 1. Generate the internal signal 'V/UHF T/R STOP TX'ING' for the V/UHF T/R FSP
2. Generate the internal signal 'HF T/R START TX'ING' for the HF T/R FSP
3. Format state response 'Transmitter active on HF' .

Action [9] 1. Generate the internal signal 'V/UHF T/R STOP TX'ING' for the V/UHF T/R FSP

Action [10] 1. Send state response 'HF T/R TX'ING'

Action [11] 1. Send state response (Transmit command ignored' to acknowledge PTT on SCC

Action [12] 1. Send state response 'V/UHF T/R TX'ING'

Action [13] 1. Send state response 'Upper Aerial selected'

Action [14] 1. Send state response 'Lower Aerial selected'

Action [15] 1. Send state response 'Squelch in'

Action [16] 1. Send state response 'Squelch out'

Action [17] 1. Interrogate bit 5 of State Control Word 1 and generate one of the following signals.-

'ACTIVE TX ON HF' - bit 5 set to '1' or 'ACTIVE TX ON V/UHF' - bit 5 set to '0'

Figure 14 Communication System FSP

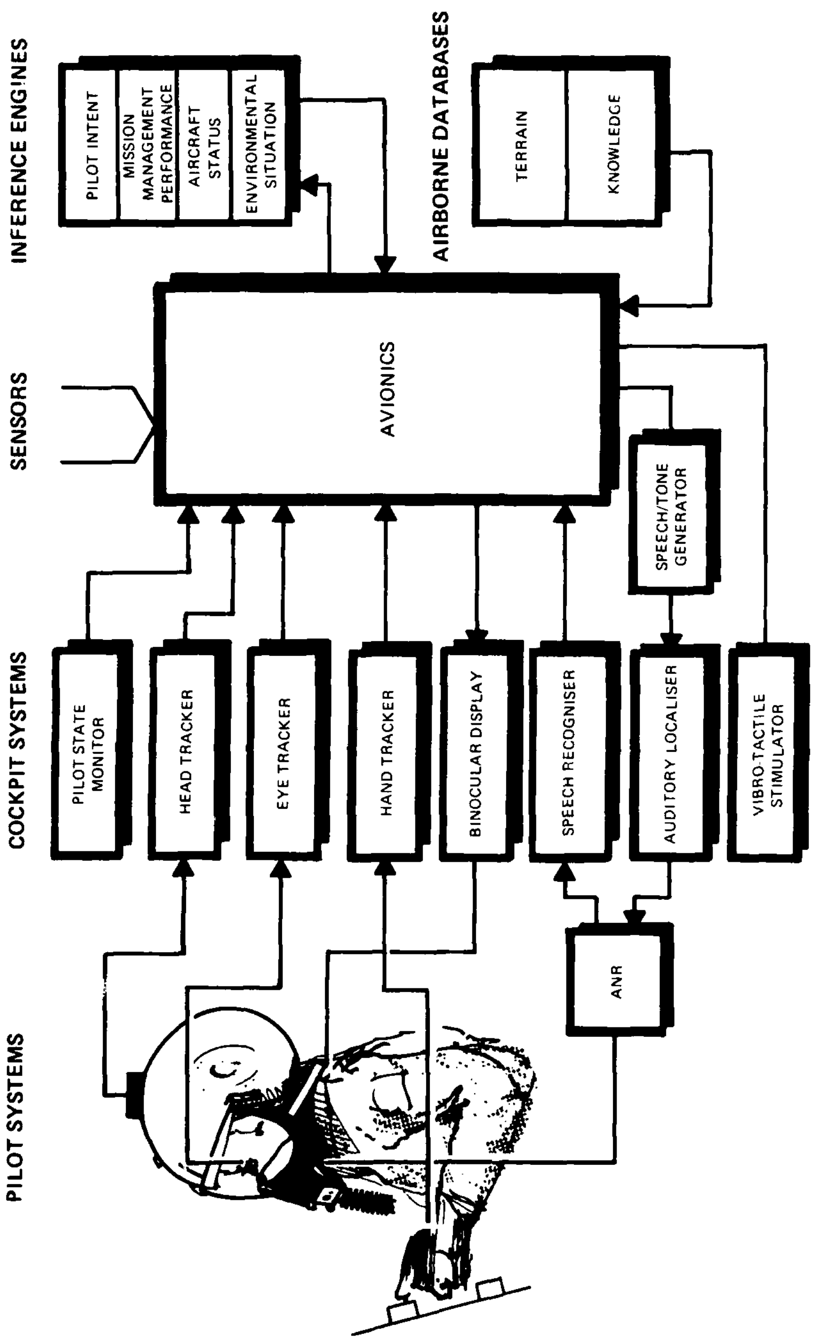


Figure 15 UK Advanced Cockpit Concept

PILOT CONTROL DEVICES

by
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SUMMARY

Advanced cockpit design requires geometry improvements to accommodate greater pilot percentile ranges, to reduce pilot fatigue and discomfort, to increase G-load resistance, and to allow a different ejection path.

Simulator trials have been accomplished to optimize the installation positions of control devices for different seat angles, the control parameters including gain and force gradients as well as the use of force and displacement signals. The simulator results will be scaled for inflight use. Adaptive gain shaping and a reduction of control forces using nigher controller damping have been tested.

A method for reducing the risk of loss of consciousness (LOC) and means to increase pilot efficiency will be discussed.

1. INTRODUCTION

Great advancements have been made in the development of mission adaptive control systems, but no serious attempt shows up to fit the pilot's environment to human requirements. Looking at present cockpit and control layout, you will find workable compromises only.

COCKPIT GEOMETRY

There are several new aspects which affect advanced cockpit design.

Anthropometric dimensions - These dimensions increase at a fairly constant rate, but the flight medical center of the German Air Force recently discovered an unproportional increase of the upper leg length. This dimension interferes essentially with the ejection clearance of the cockpit.

Seat ejection path - To avoid back injuries during ejection it is requested to have the ejection line not only parallel to the back tangent line, but rather at a negative angle (e.g. CREST program). The resulting ejection path again interferes with cockpit and windshield structures.

Pilot comfort and endurance - A seat back tangent angle of 22 degrees seems to give the most comfortable and relaxed sitting position for most of the mission phases except short range air to air combat. Using an adjustable seat in the simulator, the majority of the pilots adjusted the seat back to 22 degrees, some preferred less but no one more.

Those familiar with cockpit design know that the required anthropometric ranges cannot be accommodated at 22 degrees back tangent position by the use of center stick and standard seat height adjustment.

For the simulation trials, however, the control devices have been optimized to fit the 22 degree seat installation position because some human research development programs include better adjustable seats.

SIMULATIONS TO OPTIMIZE CONTROL DEVICE PARAMETERS

Being well aware of some fundamental divergences between simulator and inflight results in the past, efforts have been made to avoid recognized deficiencies.

Therefore every simulation setup was checked, using a very selective handling quality criterion which also includes the control forces. A lead-lag element of the flight control system was shaped in order to move the individual setups as close as possible to the optimum within the level 1 area.

To compensate the low stress and lack of motion feedback of the fixed-based simulator, a very demanding or even exaggerated pilot task was selected to enforce continuous closed loop control.

2. SIMULATOR TRIALS WITH SIDE AND CENTER STICK

The purpose of these simulations was to determine parameters and transfer gain shapings for future airborne application.

EQUIPMENT DESCRIPTION

A fixed-base simulator with HUD and a single channel visual system were used for the trials.

The total time delay including all elements was between 50 and 90 msec.

The electro-hydraulic force loader for center and side stick allowed the variation of the following parameters:

control forces	maximum velocity
displacements	dead band
force gradients	friction
breakout forces	damping

Force, displacement and rate sensing signals were available for further processing.

INSTALLATION GEOMETRY

The position of the grip reference point in relation to the neutral seat reference point (NSRP) and the operation axes of the controls were optimized in order to achieve the highest level of comfort, ease of handling and be operable within the required percentile range. The attained installation positions for both applications are shown in figure 1.

INSTALLATION POSITION Seat back tangent 22°	SIDE STICK	CENTER STICK
Grip reference point forward of NSRP	15.75 in (400 mm)	20.3 in (515 mm)
Grip reference point above NSRP	10.6 in (270 mm)	9.8 in (249 mm)
Offset right of centerline	11.8 in (300 mm)	0.4 in (10 mm)
Plane of pitch steering in relation to X axis	15° clock wise	19.5° cc
in relation to Z axis	14.5° clockwise	8° clockwise
Plane of roll steering in relation to Z axis	19° counter clockwise	0°

Figure 1

Note that the operating axes attained for the center stick installation are different from conventional use, but were positively accepted or even passed unnoticed by pilots used to standard geared center stick installations in fighter aircraft for up to 20 years.

SIMULATION SETUP

Pilot task - The pilots had to track an airborne target which was programmed to execute 40 fairly erratic maneuvers following some steady flight phases. Figure 2 shows an example of the targets flight behaviour.

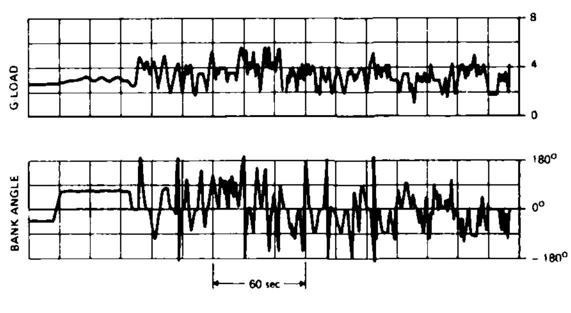


Figure 2 Target maneuvers

Frequencies and rates for pitch and roll commands were varied considerably and the maneuvers have been rearranged on a random basis, for every run, to avoid control anticipation, forcing the pilots to a closed loop interaction at any time. The task was also set up to exceed real flight situations in magnitude and duration in order to compensate the low stress fixed-base simulator trials.

Control input limitations - To minimize distractions caused by the requirement for additional control manipulations, the power control was done automatically, the rudder control disconnected and a fixed sight was used.

Selection of control parameters - Because it is virtually impossible to change all related parameters within one simulation campaign and still achieve a statistically relevant number of ratings, some factors had to be preoptimized, such as control friction, breakout forces, dead band, damping and switch-over points.

As shown in figure 3 for the side stick and in figure 4 for the center stick, a large number of positions within the initial force/gain and force/displacement diagrams have been selected to shape the total gradients used for the simulator trials.

Figure 3 also shows the recommended boundaries of previous inflight simulations downscaled for fixed base simulator use.

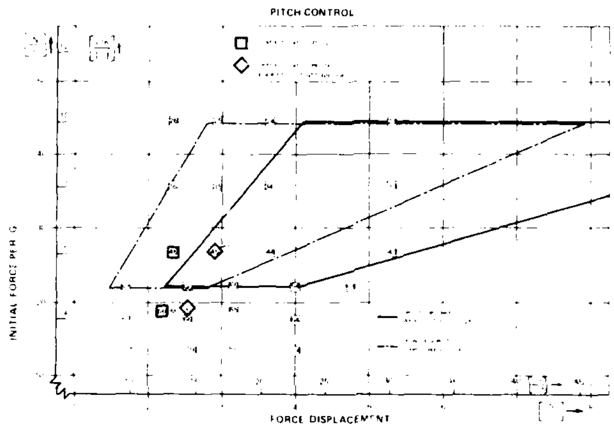


Figure 3 Side stick gradients

Figures 4 and 5 show, in addition to the selected positions, the downscaled gradients of experimental and operational fighter aircraft in use (02, 2, 04, 4) as well as the lower dynamic and static boundaries according to MIL-C-8785C.

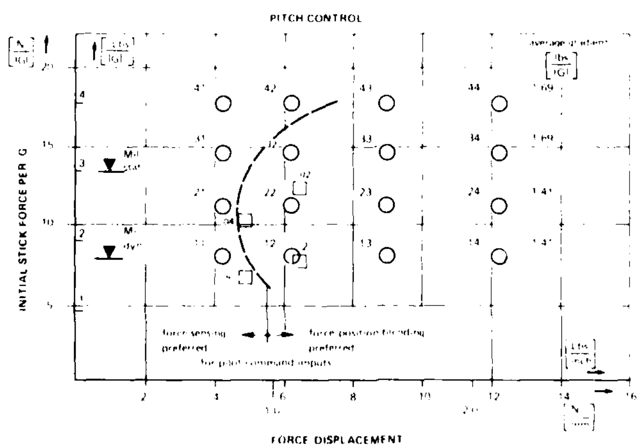


Figure 4 Center stick gradients

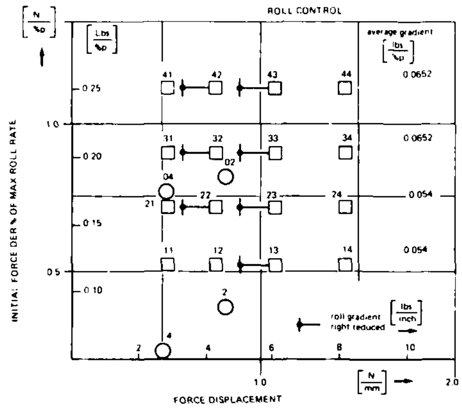


Figure 5 Center stick gradients

Gain shaping - For the initial force/gain gradients, linear slopes were used for pitch and roll command up to 8 percent of the total maneuver potential for the side stick and 15 percent for the center stick. The remaining potential is controlled via a parabolic shaped gain gradient. This approach was used to attain the necessary scaling for precision tracking in combination with acceptable force levels at the maximum maneuver points and to avoid corners at the switch-over points. These points have been preoptimized and it was amazing to see that the preferred initial force/gain gradient was larger for the side stick compared with the center stick.

Control forces and roll asymmetries - As a reference for the selection of control forces, all available information on experimental and operational fighter type aircraft have been considered. The forces for roll command inputs to the right have been reduced until both directions were reported to require similar effort (Figure 5).

Flight control system - Pitch and roll rates have been used as main control parameters with maximum attainable G-load, angle of attack and roll rate as limiting factors. During every cycle the maximum attainable loads and rates have been computed as a function of airspeed and the direction of airflow. The gain shaping then was adjusted to achieve correlation between maximum stick force/deflection and the momentary aircraft potential in any phase of flight.

By these means the flight handling characteristics are almost similar to a conventionally controlled aircraft, and any distracting dead-stick portions - with the pilot out of the loop - are avoided. Figure 6 shows an example of the force/gain shaping for the roll and pitch command signals the asymmetric roll forces and the matching to the momentary maneuvering potential give the pilot the opportunity to sense the aircraft potential without warning indicators.

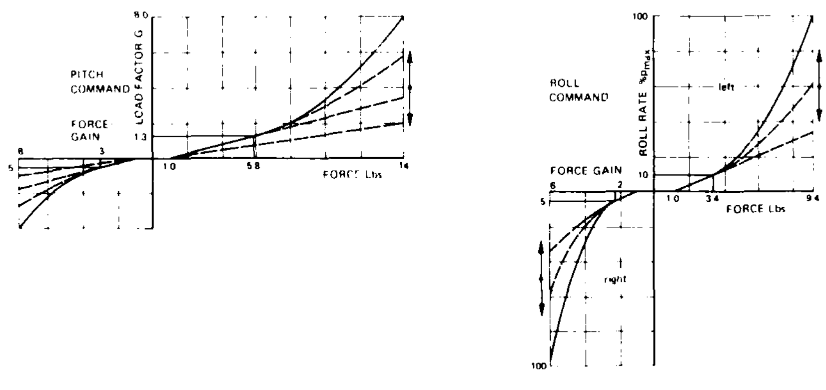


Figure 6 Example of force/gain shaping

To measure the pilots' command inputs, force and displacement sensing arrangements were available, as well as the combination of both.

Flight handling criterion - To compare stick parameters and transfer shaping it was necessary to have identical handling characteristics with changing force/gain gradients. Looking for a criterion to determine the handling qualities of a digital flight control system including control forces and aircraft parameters we found the Phase/Gain Margin Criterion the most selective (Reference 2 and 3).

Figure 7 shows the BODE plot where the Phase/Gain Margin Criterion takes the phase margin δ_m at the crossover frequency, the gain margin G_m at the 180° phase point and the maximum overshoot of the frequency response $|G|_{max}$.

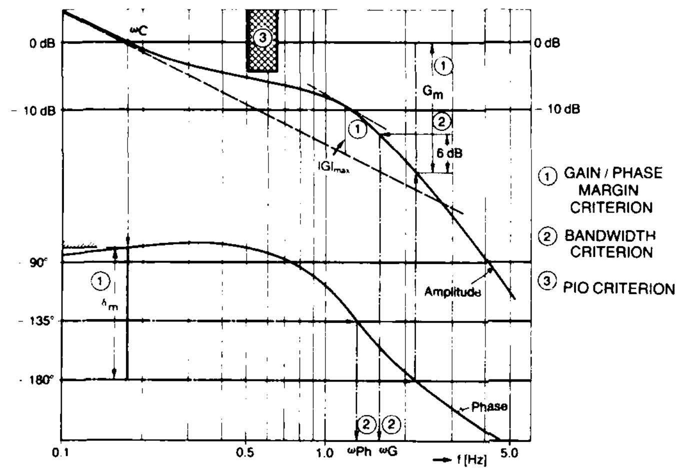
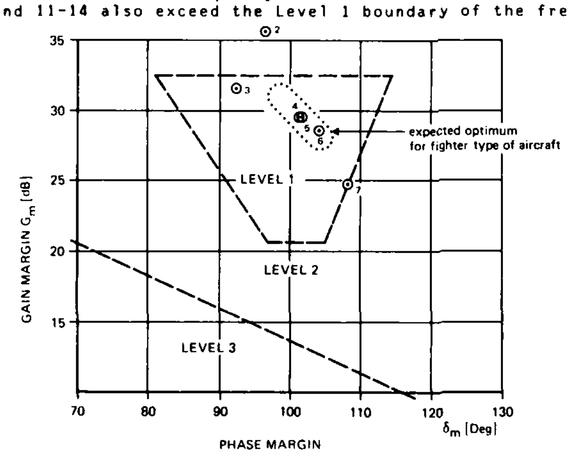


Figure 7 BODE diagram

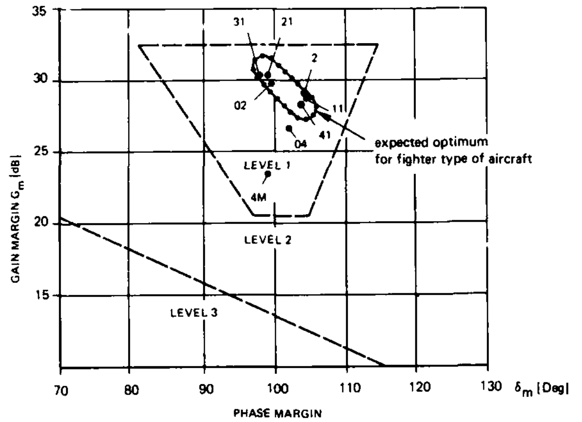
By adjusting the lead-lag element of the flight control system, it was possible to shift most of the force/gain combination to the area of the expected optimum for fighter type aircraft within Level 1 (figures 8 and 9).

For the side stick arrangement the shapings number 23-27 and 74-77 exceed the Level 1 area of the gain/phase margin diagram. Number 74-77 also exceed the Level 1 boundary of 10 dB for the maximum frequency overshoot. For the center stick the shapings number 2, 04, 4M and 11-14 also exceed the Level 1 boundary of the frequency overshoot.



Type of shaping	δ_m [Deg]	G_m [dB]	$\lvert G\rvert_{max}$ [dB]
2 = 23 ... 26	96.5	35.1	2.01
3 = 33 ... 36	92.3	32.2	3.9
4 = 43 ... 46	101.3	29.1	7.8
5 = 53 ... 56	101.4	29.1	9.6
6 = 64 ... 67	104.7	27.2	9.8
7 = 74 ... 77	108.4	24.8	12.2

Figure 8 Side stick



Type of shaping	δ_m [Deg]	G_m [dB]	ω_C [rad/sec]	$\lvert G \rvert_{max}$ [dB]
DK.02	99.480	29.7363	0.4924	8.5800
DK.2	103.8127	29.1407	0.6654	13.9883
DK.04	101.9304	26.6711	1.0817	19.0779
DK.4M	98.9399	23.6093	1.5720	22.8522
DK.11...14	104.4526	28.8845	0.6355	13.3432
DK.21...24	98.9019	30.4964	0.5254	9.9859
DK.31...34	97.5827	30.3590	0.4627	7.1676
DK.41...44	103.4325	28.4512	0.4362	6.0304

Figure 9 Center stick

SIMULATOR TRIALS

Every setup was tested to the point where the respective pilot was sure of his initial rating. Thereafter the complete target program was started and the air target had to be tracked as close as possible. After every simulator run, the pilot was asked to rate this setup using the Cooper Harper Rating and a refined Pilot Opinion Rating (figure 10).

		Level I Satisfactory			Level II Unsatisfactory			Level III Not Acceptable			Not Flyable	
		1	2	3	4	5	6	7	8	9	10	Remarks
Controls	Forces	excellent	good	quite good	accept	little heavy	heavy	too heavy	very heavy	extreme heavy		
	Compromise against		light	too light	unwanted inputs	over shoot	over load	PIO tendency	PIO onset	PIO		
	Displacement	excellent	good	quite good	accept	short little long	short long	short too long	short very long	short extreme long		
	Harmony	excellent	good	satis-factory	accept	slightly disharm	disharm	distracting	very distrac			
Response	Initial Response	ideal	good	quick adequate lagging	snappy little slow	abrupt sluggish slow	excessive too slow	very poor	bad	very bad	loss of control	
	Predictability	excellent	good	quite good	fair	adjustab	hard to adjust	very poor	bad	very bad	loss of control	
Controlability	Precision	pure	nice	quite precise	adequate	unprecise wander off	poor demands effort	very poor	unable to perform			
	Tracking	steady on target	good	satis factory	not too bad	overshoot tendency bobble	difficult	PIO tendency	PIO onset	strong PIO	loss of control	
	Coarse Maneuver	excellent	good	satis factory	abrupt little slow	bucky dig in	oscillat tendency	PIO tendency	PIO onset	strong PIO	loss of control	
Gust Disturbance	Random IFR	none	none light task	mild no problem	notice able	signifi cant	accen tuated	PIO tendency	PIO onset	strong PIO	dangerous	

Figure 10 Pilot opinion rating

Pilot background

For the side stick trials 7 pilots were available; 4 pilots were holding a class 1 flight test rating and 3 are experienced military fighter pilots. Approximately 80 hours of simulator time was used.

The center stick trials have been accomplished by 10 pilots - 4 flight test and 6 operational military pilots. A total of 110 hours of simulator time was used.

The individual rating as an average of the Cooper Harper and the Pilot Opinion Rating and the average ratings of all pilots are shown in figure 11 for the side stick and in figure 12 for the center stick.

In addition to the individual ratings, 10 task related parameters have been collected at every computation cycle and accumulated over the total task period to see whether there was any correlation between individual ratings and obvious tracking deviations.

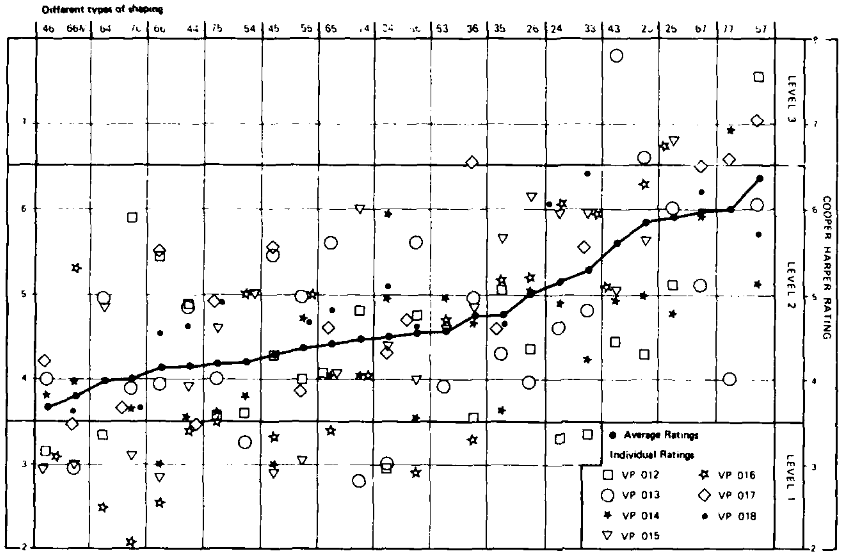


Figure 11 Side stick ratings

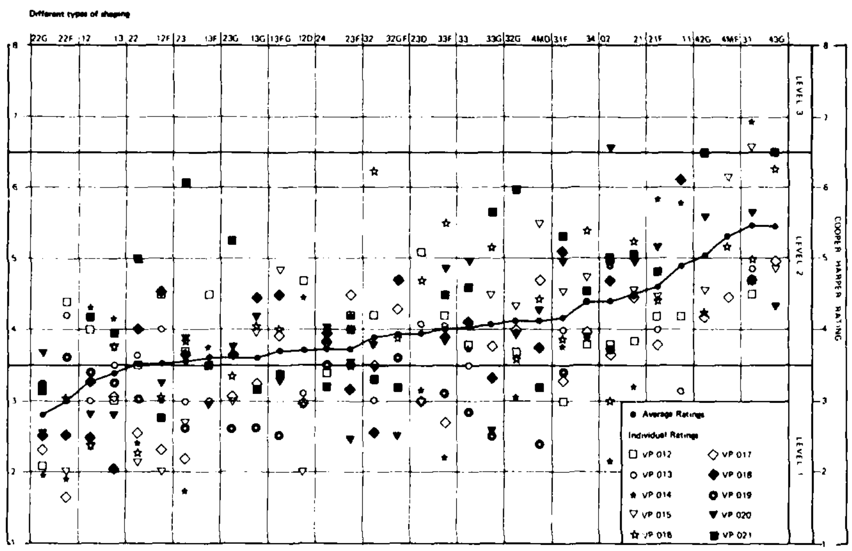


Figure 12 Center stick ratings

DISCUSSION OF RESULTS

Compared with similar simulation trials the spread of the individual ratings can be considered normal. But as the number of pilots gave a sufficient data base, the average ratings point fairly straight towards a specific area of the force/gain and force/displacement diagrams.

There are two possible explanations for the relative, low overall rating

- The tracking task was exaggerated on purpose to enforce closed loop control
- Some roll/yaw coupling effects of the aircraft model which were slightly distracting especially during rapid reversals.

Side stick - It was amazing to see that the best ratings among the side stick results showed up for the initial force/gain ratio of 4 and 6 Lbs/G in the area of 15 to 17 Lbs/inch for the force/displacement but the setups at 5 Lbs/G were downgraded (figure 3). The reason of these rating deviations was uncovered to be that, because of the shapings of force/gain and force/displacement gradients, the displacement/gain gradient ended up with a reversion point. Thus we learned that the human controller is not only sensitive to force/gain shaping but to displacement/gain shaping as well.

Another main difference between the best rated shapings number 46 and 66 M was an increase of damping for pitch command input by a factor 10 for number 66 M.

During the side stick trials mainly the force sensing signals were used to drive the flight controls system but some tentative simulations showed that a mix of force and displacement signals would improve the ratings.

Center Stick - The center stick simulations showed the best average rating at approximately 2.5 Lbs/G for the initial force/gain ratio and 7 Lbs/inch for force/displacement. For most setups a 12 times higher damping factor for pitch control compared to roll control and a blended force/displacement sensing signal was used (figure 13). The forces for roll input right were reduced and a noticeable difference between the dead band required for pitch and roll commands was discovered.

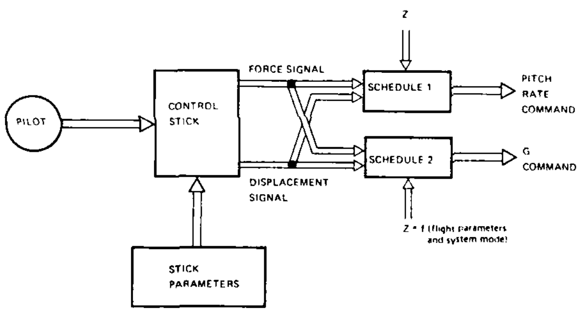


Figure 13 Force/displacement blending

The additional letter markings behind the shaping numbers in figure 12 stand for:

D ... equal damping for pitch and roll commands
F ... force sensing signal only
G ... reduced force/displacement gradients for roll inputs to the right.

During the first portion of the simulation trials setups which attained level 3 ratings were dropped.

After continuous comments like "forces to the right feel heavy and not harmonized" with a reduction to 66 percent of the forces for left roll commands, the force/displacement gradient to the right was reduced maintaining the previous forces until it felt equal in both directions.

Comparison between side and center stick results - Looking at the diagrams of figure 14 and 15 which show the best rated simulator solutions scaled for inflight use, some remarkable differences can be seen:

Initial force/gain ratio

5.1 Lbs/G for the side stick
3.75 Lbs/G for the center stick

Forces

Slightly higher forces for the center stick for pitch steering but smaller forces for roll control compared to the side stick.

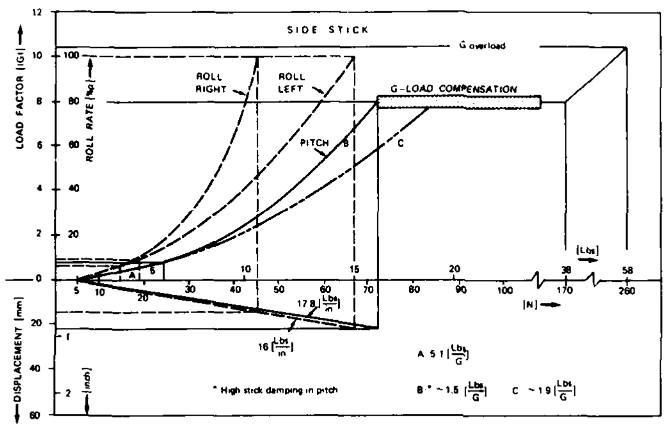


Figure 14 **Side stick results scaled for inflight use**

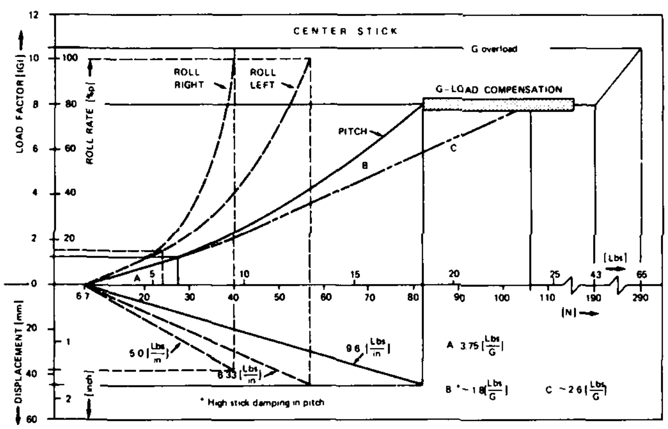


Figure 15 **Center stick results scaled for inflight use**

Displacement

In general, the displacement for the center stick turned out to be twice the size compared with the side stick, 1.7 inch (44 mm) versus 0.8 inch (21 mm) for pitch and left roll.

Force/displacement ratio

The side stick gradients for pitch and roll deflections are almost identical and show no differences between left and right roll steering. For the center stick, a definite reduction from pitch to left roll and to right roll input can be seen.

3. RECOMMENDATIONS FOR INFLIGHT USE OF G-LOAD COMPENSATION

Figures 14 and 15 depict an area marked G-LOAD COMPENSATION. This, of course, was not tested in a fixed-based simulator, but figure 16 shows the dip of the human load factor tolerances starting at the point where residual oxygen is no longer sufficient to the point where body compensation takes place. A workable solution to get around this dip and avoid or compensate the pilot's loss of consciousness is to program the flight control system to reduce the initially commanded G-load automatically, along a present time scale to a more tolerable level, unless the pilot is overriding this function with increasing control force. In this manner the flight path behaviour is also similar to a dynamically stable aircraft.

Until the moment when unmistakable medical indications of approaching LOC were discovered, this type of load compensation could be used mainly because the muscle tension was found to be kept constant for an extended period of time after LOC occurred.

To command emergency G-load conditions or angles of attack in excess of maximum lift, further increase of control force will be required.

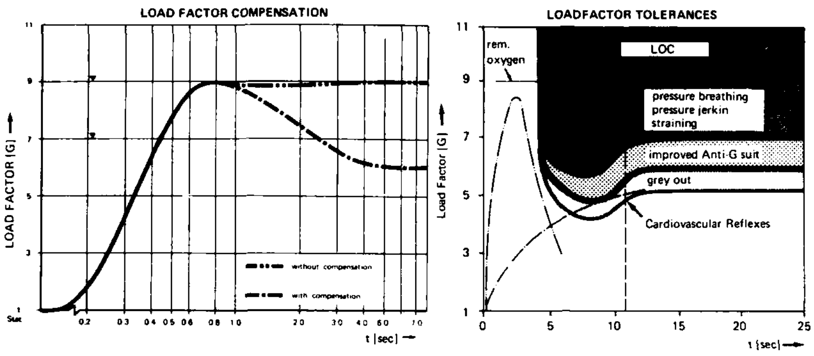


Figure 16 Example of G-load compensation

MECHANIZATION OF CONTROL DEVICES

During the simulation trials all parameters have been used and optimized from the point of view of simple and inexpensive mechanization for inflight use to avoid additional equipment and systems being installed, just to generate unnecessary sensations to the operator.

Friction was reduced to a point which may be expected from the mechanized device. Velocity limit was set to a setting where it had no influence on the rating. It also was found that varying slopes for the force/displacement gradients were not required.

Damping was kept at a constant value and differed only for pitch and roll control.

Therefore only a simple spring and damper arrangement is required for airborne installations.

Blending of force and displacement signals - The simulations showed that the blending of signals improved the handling of momentary response and precision tracking for most of the gradient combinations.

Figure 17 shows a scheme of the signal shape as a function of rate and damping. Plots showed up to 70 msec spacing between signals at maximum manual input rate. This indicates that there is room for optimizing the system to the pilot inputs - especially rate and size - to fit the momentary aircraft potential and the pilot's intentions.

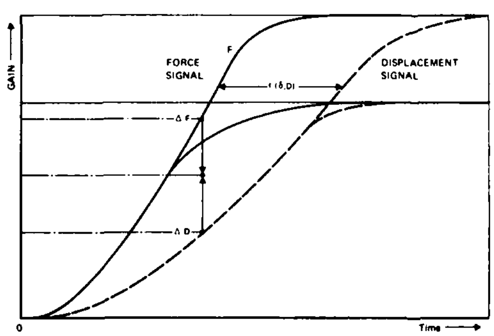


Figure 17

Safety aspects - As the installation position of force and displacement sensing transducers may well be separated and either package is sufficient for aircraft control, there is additional redundancy in case of damage. Even a totally stuck controller will allow aircraft control at slightly degraded modes.

Active control devices - Using optimized signal blending and gain shaping an advantage for the application of an active control device is not visible, only disadvantages, viz. extra weight, cost, complexity, additional time lags and flight safety risks.

Arm rest - The center stick installation should be arranged to give the majority of the pilots the chance to rest their arm on their right upper leg.

For side stick installations an armrest is mandatory. The armrest has to be adjustable to fit all anthropometric dimensions and compensate normal and sideloads. Up to this point, it was self-explanatory, but simulations showed that tracking performance as well as pilot ratings improved with an armrest installation that supported but did not lock the natural geometry of movement. At the same time it was found that the movement of the armrest must by no means introduce additional motion patterns.

This may require adjustable pivot points and well defined force/displacement gradients for maximum pilot comfort.

4. INCREASING PILOT EFFICIENCY THROUGH WORKLOAD REDUCTION

Information display and system handling - Due to increasing specialization and diversification of equipment suppliers as well as new or additional system functions, we see a culminating tendency to increase the number of information and controls in the cockpit. This increase of workload causes a decline of pilot efficiency.

The introduction of data entry keyboards optically reduced the number of controls and switches but did not reduce workload because the pilot has to memorize codes and is forced to identify optically numerous push-buttons which takes more time than flicking a designated switch.

Therefore we must look at any system function and information requirement for the primary and secondary mission to identify sequential, parallel or commonly triggered functions to reduce the controlling effort.

If, for example, the pilot wants his aircraft to be electromagnetically silent, it does not make sense to page half a dozen system layouts to the displays trying to identify the respective RECEIVE ONLY switch, whereas a single button press 'SILENT-ON' as HOTAS function can take care of all active systems at the same time.

Any detailed analysis of system functions and operational requirements will uncover numerous possible interconnections and means to streamline the controlling effort to improve pilot efficiency.

Data input inflight must be kept at an absolute minimum, which means manual entry of frequencies and codes for communication, navigation or identification will not occur during a standard operational mission. Every effort must be made to have sufficient permanent and premission storage capacities available and have the required data either automatically available or easily accessible.

Tentative research work at our simulator shows that Direct Voice Input may be a useful means for data input but only under relaxed environmental conditions and not on a routine basis.

HOTAS functions - Parallel to automatic system functions optimized HOTAS arrangements are considered the best means to increase pilots efficiency. But on the assumption that the hand position at stick and throttle tops must not change and all switches must be accessible throughout the anthropometric range, only a limited amount of functions is available. In addition, switch handling must not interfere with aircraft control and simultaneous switching functions at the same grip should be avoided.

In order to have immediate, unrestricted and unobstructed access to any switch - which is of vital importance especially during air to air operations in a multi-bogey environment - no additional safety covers or guards (like late arm switches etc.) can be tolerated. The required operating speed for associated functions in combination with rapidly changing body positions, introduces the risk of repositioning these obstructions. Which means the switch functions are not available if required and there may be no second chance.

Figures 18 and 19 show possible arrangements and functions. Especially the 4 and 5 position switches and force transducers allow various related functions, e.g. combined control of sensors, seekerheads, HUD, head-down display and helmet mounted sight.

These stick and throttle tops are in operation at the simulator cockpit. Future trials will be required to achieve the integration of main function and deviations thereof.

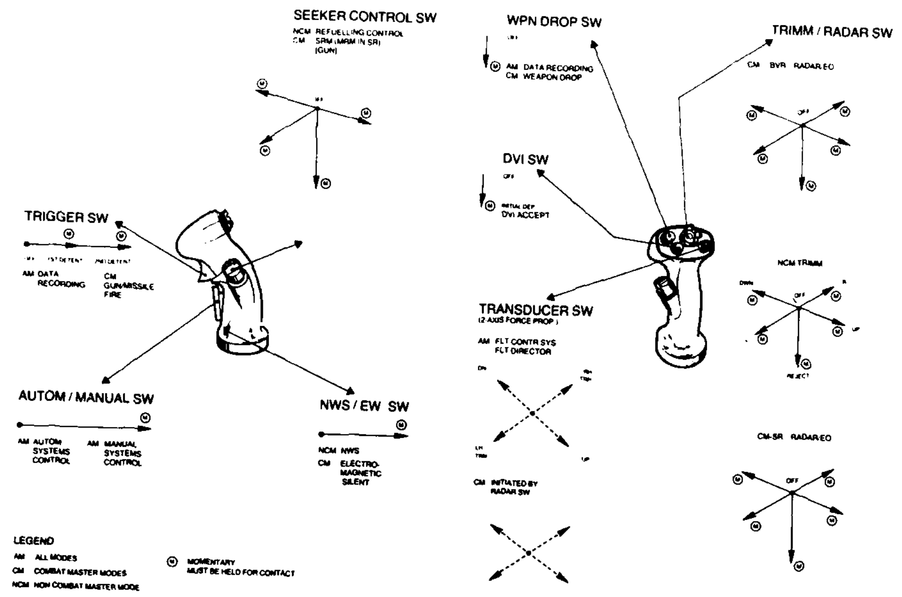


Figure 18 Stick tops for HOTAS function

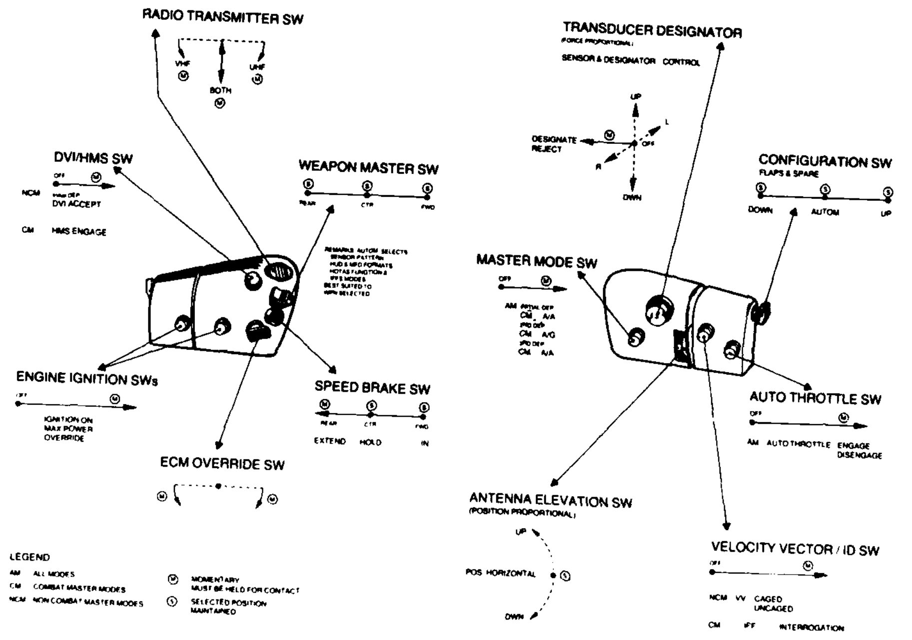


Figure 19 Throttle tops for HOTAS function

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ACTIVE AND PASSIVE SIDE STICK CONTROLLERS: TRACKING TASK PERFORMANCE AND PILOT CONTROL BEHAVIOUR

by

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SUMMARY

A servo controlled side stick featuring hydraulic actuators with hydrostatic bearings was developed at Delft University of Technology. Due to its smooth operation, low noise characteristics and high bandwidth (70 Hz.), a great variety of dynamic characteristics (apparent mass, damping and spring force gradient) can be simulated. This research tool can very conveniently be used as a conventional "passive" stick to assess, for instance, the desired side stick dynamics for future Fly By Wire aircraft.
Still more important is that with a servo controlled side stick, stick force and stick displacement can be controlled virtually independent. This characteristic can be used for experimental research to investigate the perception and feedback of stick force and stick displacement by the pilot's neuromuscular system in the control task.
After a short description of the side stick controller hardware, results of a tracking experiment in the Aerospace Faculty's moving base flight simulator will be presented. In this experiment the side stick was used as a passive as well as an active (aircraft output feedback via the stick position) controller. Considerable improvement in tracking performance and significant changes of measured pilot control behaviour were found for the "active" when compared to the "passive" control stick.

1. Introduction

A recent paper by Johnston and McRuer on Limb-Side Stick Dynamic Interaction on Roll Control gives a review on the problems encountered in almost every new aircraft with Fly by Wire control systems. See Ref. 1. Pilot induced oscillations, roll ratchet, biodynamic interactions, etc., are well known problems often highlighted in literature during the last decade. Interaction of the high performance flight control systems and neuromuscular system dynamics seems to be the major cause of these problems. Besides the roll control problem just mentioned, it is known that the development of the side stick in the Fly by Wire controlled Airbus A 320 did raise many questions from the evaluation pilots of the airlines and still does so.
At the Faculty of Aerospace Engineering of the Delft University of Technology a long term research program directed to a better understanding of pilot's behaviour in aircraft control was started around 1980. The program is especially directed at the information processing by the pilot when controlling the aircraft. Since the information processing by the human controller starts with perception, the research program was initially aimed at the perception of the motion state of the aircraft. This work provided insight in motion perception from central and peripheral visual cues (instruments and outside word) and vestibular (motion) cues but also provided methods and experience in investigating the pilot's use of these resources when performing his task. See Ref. 2.

After the success of the initial program on motion perception a second program directed on pilot's control was started. It was realized that in order to investigate the control behaviour - especially the way the pilot generates his control output and how he reacts on the perceived stick force and stick displacement - a special manipulator had to be built to obtain the possibility of modulating subject's control output during laboratory experiments. It was decided that a servo controlled side stick was most appropriate for this purpose. The advantage of such a manipulator is that the stick force and stick displacement can be made independent. This yields the possibility to influence subject's output generation. Given the broad experience on electro hydraulic servo systems available at the University, obtained with flight simulator motion and loading systems, the development of a electro hydraulic servo controlled side stick was started. Electro hydraulic servo motors have the advantage of a high bandwidth ($\omega_e \geq 50$ Hz.) of the position control system and therefore can generate fast changes of stick position.

With such a side stick the following research subjects can be tackled:
- static and dynamic characteristics of the neuromuscular system of the arm
- design criteria for side sticks i.e. zero position, maximum deflection, breakout forces, spring stiffness, damping etc.
- the use of the side stick as a passive or active manipulator.

The first step was to develop a single axis servo controlled side stick based on a modified servo motor of the electro-hydraulic control system of our laboratory aircraft. In addition a literature study on the ergonomic aspects of side stick controllers was performed. See Ref. 3. Some experience with that single axis side stick was obtained and is reported in this paper.
After the design of the single axis side stick control system was completed, see Fig. 1, a two axis side stick was developed which side stick is now available for research. See Fig. 2.

So far two experiments have been performed with the single axis side stick. One was directed to the perception of static values of stickforce and stick displacement. This study showed clearly the asymmetry in the sensors of the neuromuscular system when perceiving static stick force and displacement in the roll axis.
The second experiment was a tracking experiment to investigate the influence of the feedback of perceived stick force and stick displacement on the tracking behaviour of the subjects. As will be shown in this paper a remarkable change in control behaviour and performance can be obtained if suitable variables are fed back to the subject by way of the stick position.

In the next chapter the principal difference between passive and active side sticks will be discussed. In chapter 3 the test facility and in chapter 4 the tracking experiment will be described. The results are given in chapter 5 and in chapter 6 the conclusions will be drawn after a short discussion.

2. Passive and Active manipulators

In the tracking experiment reported in this paper, the side stick was applied as a passive and as an active controller.
Before going into the details of the tracking experiment, it seems appropriate to stress the distinction between the two controllers. When a servo controlled manipulator is used to simulate the dynamic characteristics, breakout forces, etc. of a side stick as used in a fly by wire controlled aircraft, such as the F 16, then it may be called a passive side stick. In Fig. 3. it is shown how a passive, servo controlled side stick fits in the control loop. The measured stickforce is the input to the model of the side stick dynamics in a computer. The stick displacement, the model output, is the control signal to the aircraft, as well as to the position control loop of the side stick.

In the last ten to fifteen years research has been performed at a number of research institutes on the subject of so called active controllers. See Refs. 3, 4, 5 and 6. Although the meaning of the term "active controller" may vary among authors, common to all active controllers reported in literature is the use of a servo system for the control of the manipulator. In this paper the term "active" is used when the stick force is the input to the aircraft control system and an aircraft state or output variable is the input to the position control of the side stick. See Fig. 4.
In case of a passive side stick the side stick deflection is the control input, whereas in case of an active stick the deflection is proportional to system output or an arbitrary combination of state variables.
Stated differently, see Fig. 3. and 4, with a passive side stick a pilot feels simulated stick dynamics. With an active side stick, he "feels" aircraft dynamics, since they are included in the feedback loop. (If control surface deflection is considered as an aircraft state variable then conventional mechanical controls would fall into the category of active controllers.)
If, for instance, the lateral deflection of an actual side stick is equal to aircraft roll angle and the lateral stick force is the input to the roll control system, then the pilot can stabilize the roll angle by holding the stick in a fixed position. A deviation of the aircraft roll angle will give a deflection of the side stick. The pilot will automatically exert the appropriate force on the stick and correct the roll angle deviation by simply holding the stick fixed in the same position. One might say that the pilot virtually holds the aircraft in his hand.
By including the active side stick in the tracking experiment, a comparison of the different feedback methods of passive and active side sticks, in one experiment, could be made.

3. Test facilities

The experiment was performed in the research flight simulator of the Faculty of Aerospace Engineering of the Delft University of Technology. See Fig. 5. In order to limit the number of experimental conditions in this preliminary experiment, the motion system of the simulator was not used. The subject was seated in the right hand seat and held the side stick in his right hand. See Fig. 6. The system dynamics of the roll control task was a double integrator (K/s^2), see chapter 4. The roll angle was displayed on a CRT display (simulated artificial horizon) in front of the subject. See Fig. 6.

The manipulator used in the experiment was a single axis servo controlled side stick already mentioned in the introduction. See Fig. 1. The position servo was an electro hydraulic servo motor with hydrostatic bearings with a Coulomb friction of approximately 1 Newton. The maximum deflection of the side stick was ± 30 degrees. The position of the servo motor piston rod is measured by using a L.V.D.T (Linear Variable Displacement Transducer). The control of the servo motor was obtained with a Moog electro-hydraulic control valve. The position control loop is shown in Fig. 7. and the electronic components of the control loop are positioned close to the side stick. The dynamic characteristics of the position control loop can be described by a second order system with a natural frequency ω_0 = 70 Hz and a damping ratio ζ = 0.5. The measured transfer function is shown in Fig. 8.
The stick force is measured with strain gages so that they are sensitive only to a force exerted laterally on the stick and not sensitive to a moment. In case of a simulation of a passive side stick, the stick force is the input to the side stick model. This model may include second or higher order dynamics and non-linear components such as a breakout force.

If the dynamic characteristics of the simulated side stick can be described by a second order system then:

$$F(t) = m\ddot{y}(t) + w\dot{y}(t) + cy(t) \qquad (3.1)$$

where F is the stick force and y is the position of the piston rod of the servo motor. Due to the geometry of the side stick the transfer function describing the relation between the stick displacement s_a in degrees and the stick force F_a in Newtons is:

$$\frac{s_a(s)}{F_a(s)} = \frac{1000}{ms^2 + ws + c} \qquad (3.2)$$

where in: m = simulated mass
w = simulated damping
c = simulated spring stiffness

For stability the simulated mass m and damping are limited to: m ≥ 0.5 kg and w ≥ 5 Nsec/m.
The spring stiffness can be varied over a wide range of values, provided that the natural frequency of the simulated dynamics remains well below the natural frequency of the position control loop (ω_0 = 70 Hz). See for a summary of details Table 1.

Passive or active side stick dynamic characteristics were simulated with the analog part of a EAI Pacer hybrid computer.

A Textronix 604 CRT display was used to display a simple artificial horizon. See Fig. 6. The repetition rate was 250 times per second. Th image was generated by the analog part of the hybrid computer.
The digital part of the hybrid computer was used to control the experiment, to generate the forcing function, to record the measurements during the performance of the control tasks and to process measured data.

4. The experiment

The aim of the experiment was to compare the subject's performance and control behaviour in a tracking task using the servo controlled side stick simulating different side stick dynamic characteristics and to investigate the influence of stick force and or stick displacement feedback. The rather academic dynamics of the roll control task (equal to those of a double integrator (K/s^2)). were chosen simply because much experimental data is available in the literature, see Ref. 8 and 9. In this way results could be compared with others obtained with the same system dynamics.
Two distinct control tasks were used in the experiment. In the first, the disturbance task, the disturbing function was made to act on the controlled system, as shown in Fig. 9. This task is quit comparable to the case in which the pilot stabilizes an aircraft in turbulent air. In the second control task, the target following task, the displayed signal on the artificial horizon e_ϕ is the difference between the forcing function i and the roll angle ϕ of the controlled system. See Fig. 10.

Three passive side sticks with different dynamic characteristics and two active side sticks were used in the experiment. See Table 2.
The first passive side stick is a simulation of a isotonic or position stick. It is simulated by a second order system with a spring stiffness equal to zero and a mass m = 0.5 kg and damping w = 5 Nsec/m. The describing function between the input stickforce F_a and the output stick deflection s is:

$$\frac{s_a(s)}{F_a(s)} = \frac{2000}{s(s + 10)} \qquad (4.1)$$

The second passive side stick is a simulation of a hardware manipulator developed by the National Aerospace Laboratory N.L.R. in Amsterdam for research applications. See Ref. 10. The static relation between stick force and stick deflection is given in Fig. 11. Between ± 18 degrees stick deflection the dynamic characteristics can be described by:

$$\frac{s_a(s)}{F_a(s)} = \frac{K}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \qquad (4.2)$$

where in ω_0 = 20.8 rad/sec and ζ = 0.95.

The third passive stick was a simulation of a isometric or force stick by simply keeping the stick deflection fixed to zero.
The input signal for the system to be controlled in case of the isotonic and NLR stick is the stick deflection, while the stick force is the control input in case of the force stick.

The stick deflection of the two active side sticks used in the experiment were proportional to the roll angle ϕ or the roll rate $\dot{\phi}$. The choice of the roll angle ϕ will be clear from the example given in chapter 2. With the feedback of the roll rate $\dot{\phi}$ to the side stick position, the subject feels the roll rate of the simulated aircraft dynamics via the stick displacement. The control input for the system to be controlled was the stick force F_a.

The gain of the system to be controlled $H_c = K/s^2$ was K = 4 when the stick deflection s_a was the control input and K = 12 when the stick force was the control input.

The forcing function consisted of the sum of ten sinusoids whose frequency, amplitude and phase are given in Table 3. The standard deviation of the forcing function was σ_i = 1.875 degrees.
Two subjects, one university student with a commercial pilot license and experience on general aviation aircraft and one university staff member, qualified jet transport pilot, volunteered in the experiment. Extensive training was done until stable performance, as expressed by roll angle or roll angle error standard deviation was reached.
All ten experimental conditions, five side sticks and two control tasks, were performed during the final measurements. Both subjects performed the disturbance task, one subject the target following task. Five replications of each combination (side stick, control task and subject) were recorded. In total 5x2x5 = 50 runs for the disturbance task and 5x1x5 = 25 runs for the following task were recorded and analysed.

Each run lasted 110 seconds of which the last 82 seconds were recorded. From each run the standard deviation of the control signal, F_a or s_a and the standard deviation of the roll angle ϕ or roll angle error e_ϕ were computed. In addition the subject's transfer function $H_p(j\omega)$ between subject's input and output was computed. From the open loop transfer function $H_pH_c(j\omega)$ the crossover frequency ω_c and the phase margin ϕ_m were determined.

5. Results

In Fig. 12. the standard deviations of the roll angle ϕ or the roll angle error e_ϕ and those of the control signal F_a or s_a are given for both control tasks and the five simulated side sticks. For both control tasks with the passive side sticks the subjects have the best tracking performance with the force stick. Active side sticks show a distinct improvement in tracking performance relative to the passive side sticks. Better performance also corresponds with a decrease of the standard deviation of the stickforce (control input). Performance improvement with the active sticks in the disturbance task could be expected because subjects can stabilize the controlled system by simply holding the stick fixed in the mid position.
In the target following task however, the subject has to follow the forcing function i. Given the small value of the standard deviation of the roll angle error, it must be conceived that the feedback of the roll angle or roll rate in the position of the side stick distinctly gives the subjects extra information which they apparently use to improve their tracking performance. The standard deviation of the roll angle for both active side sticks is approximately equal to the perception accuracy found in perception experiments with the same artificial horizon display. See Ref. 11. Hence accuracy of the performance obtained seems to be limited by the perception accuracy.

The dynamic behaviour of the subjects changed only slightly due to the different dynamics of the passive side sticks, as shown by the open loop describing functions in Fig. 13. As could be expected from the results of experiments reported in the literature, see Ref. 1, the gain and phase of the open loop describing function for the force stick provides the highest phase margin and gain margin.
The dynamic behaviour of the subjects changed considerably when changing from the passive to the active side sticks. This is clearly demonstrated by the changes in gain and phase of the open loop describing function $H_pH_c(j\omega)$ in Fig. 13. These changes lead to an increase of the crossover frequency ω_c and/or phase margin Φ_m as shown in Fig. 14. The large difference in phase margin Φ_m between the active side sticks with roll angle ϕ and roll rate $\dot{\phi}$ feedback is not surprising bearing in mind that in the frequency domain roll rate leads roll angle by 90 degrees. In the disturbance task the phase margin remains approximately equal for all five side sticks, while the crossover frequency increases. For the target following task the changes in the crossover frequency and phase margin are just reversed. This phenomenon is also found due to the influence of cockpit motion cues although it is stronger with the active side sticks than with motion. See Refs. 2, 9 and 13.

6. Discussion and conclusions

The results of the experiment presented in the present paper show that a servo controlled side stick, as developed at the Faculty of Aerospace Engineering of the Delft University of Technology, provides the possibility to simulate a wide variety of passive side stick dynamics. This offers the opportunity to evaluate proposed side stick dynamics for future Fly by Wire aircraft.
In addition it has been shown that, when using the servo controlled stick as an active controller, feedback of aircraft state or output variables offers a possibility for improvement of handling characteristics and workload reduction which is worthwhile to investigate further.
Looking in more detail at the results of the experiment it is clear that changes in feedback, from passive to active, via the neuromuscular system have a direct influence on subject's control behaviour. This is basically not due to the change in the feedback path, but due to the characteristics of the neuromuscular system, a "smart" system which may be used more effectively in aircraft control. More fundamental research is necessary to understand the way the neuromuscular system interacts with the information processing the pilot performs in aircraft control. The physiology of the neuromuscular system is well known but speed and influence of the feedback of the stickforce and stick position on the perception and control of the aircraft state is still unknown.
As shown by the results of the experiment described in this paper, the use of an active side stick in a tracking task provides the subject with distinct information which he can not obtain with his visual system from the artificial horizon display. This observation is not sufficient to explain why proper feedback of a state variable in the position of the manipulator helps the subject to improve his control.
There is a striking similarity of the influence of the addition of real motion cues to the artificial horizon display, see Refs. 2 and 9, and the change from a passive to an active manipulator on the change in subjects dynamic behaviour and performance. The same changes in subject's performance and transfer function and corresponding crossover frequency ω_c and phase margin Φ_m were found for both the disturbance task and the following task as in the present experiment, see Fig. 15. It has been shown, see Ref. 2, that in case of the addition of motion cues the improvements are mainly caused by a more direct and faster perception of rate, enabling subjects to generate lead and/or to decrease their effective time delay. In the normal frequency range of aircraft movements the output of the vestibular system leads the rotational rate signal, as it has to be perceived from the artificial horizon or the outside world, by approximately 150 msec. Given the increase of the phase angle as shown in Fig. 13 when comparing the active side sticks with the force stick, a tentative conclusion could be that the change in control behaviour of the subjects between the use of the passive and the active manipulators is caused by a lead of the neuromuscular feedback of the controlled variable relative to the visual feedback.

Summarizing the results of the tracking experiment as described in this paper it can be concluded that:

- a servo controlled side stick is an ideal tool for the evaluation of proposed passive side stick dynamics.
- active side sticks (feedback of aircraft state variables in the stick position) offer the possibility of improved handling characteristics and workload reduction which has to be investigated further.
- the improved tracking performance and increased lead in pilot's describing function due to the active side stick seems to be a result of the dynamics of the neuromuscular system.

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Table 1. Details of the position servo.

MOTOR			
piston mass	m =	0.495	kg
piston surface	A =	$0.15\ 10^{-3}$	m^2
maximum stroke	S =	0.06	m
max. piston velocity	$\dot{y}$ =	0.47	m/s
max. force (restricted)	F =	100	N
hydraulic pressure	p =	210	Bar
CONTROL VALVE			
Moog series 30 type 235A			
natural freq.	ω_0 =	1050	rad/s
damping	ζ =	0.90	
max.flow	Q =	$7.0\ 10^{-6}$	m^3/s
POSITION TRANSDUCER			
Hottinger Baldwin Messtechnik L.V.D.T. type W 50 K (0.2)			
gain	K =	120	V/m

Table 2. Side stick configurations used in the tracking experiment.

	type	description	transfer function
P	passive	position stick	$\frac{s_a(s)}{F_a(s)} = \frac{2000}{s(s+10)}$
N	passive	NLR stick	$\frac{s_a(s)}{F_a(s)} = \frac{K}{s^2 + 2\zeta\omega_o s + \omega_o^2}$
F	passive	force stick	$s_a(s) = 0$
ϕ	active	roll angle feedback	$s_a(s) = \phi(s)$
$\dot{\phi}$	active	roll rate feedback	$s_a(s) = \dot{\phi}(s)$

Table 3. Frequency, amplitude and phase angle of the components of the forcing function.

frequency ω rad/sec	amplitude degrees	phase ϕ degrees
0.153	1.106	4
0.230	1.099	151
0.383	1.083	43
0.537	1.058	122
0.997	0.957	324
1.457	0.842	184
2.378	0.646	281
4.065	0.428	194
7.440	0.247	162
13.576	0.136	43

Fig. 1. The single axis servo controlled side stick.

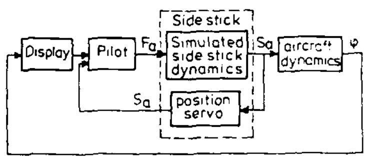

Fig. 3. Control loop with a servo controlled side stick as a "passive" controller.

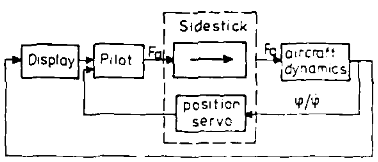

Fig. 4. Control loop with a servo controlled side stick as an "active" controller.

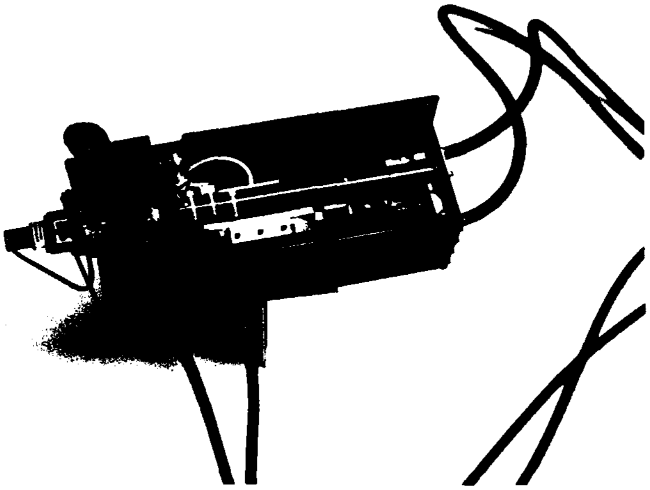

Fig. 2. The two axis servo controlled
side stick.

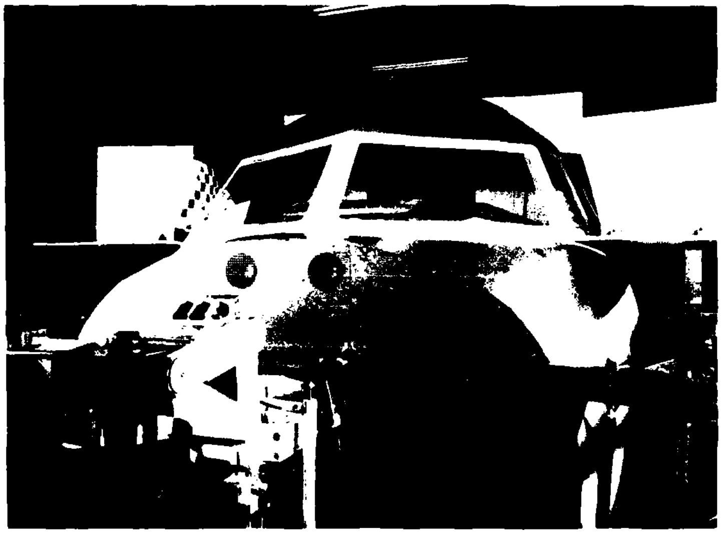

Fig. 5. The flight simulator.

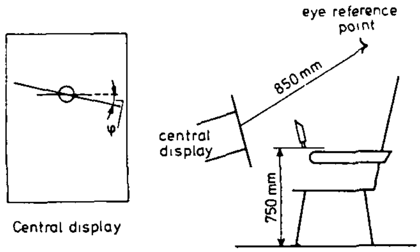

Fig. 6. Positions of the display and side stick relative to the subject's seat.

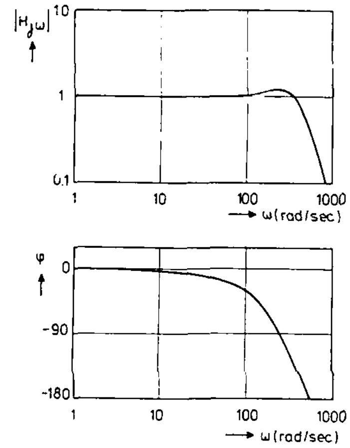

Fig. 8. The describing function of the position control of the single axis side stick.

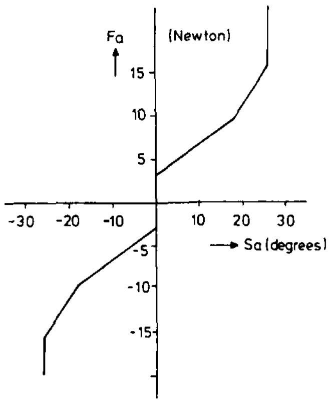

Fig. 11. Stick force as a function of stick deflection of the simulated NLR side stick.

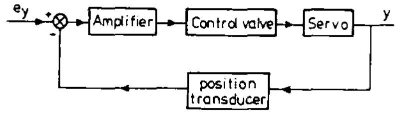

Fig. 7. Position control loop of the single axis side stick.

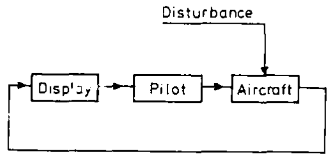

Fig. 9. The disturbance task.

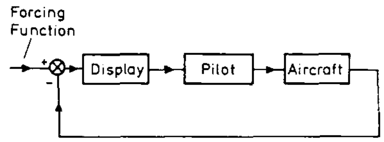

Fig. 10. The target following task.

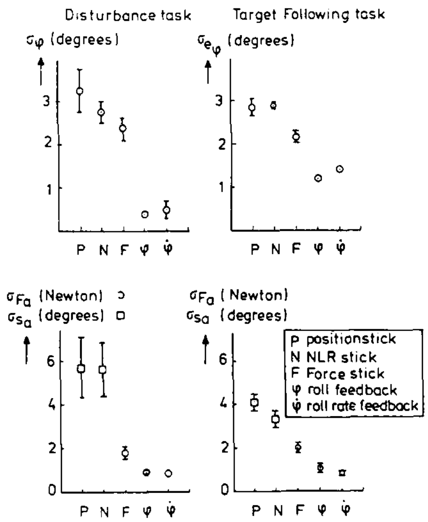

Fig. 12. Mean standard deviations of the controlled variables and control signals as measured in the experiment.

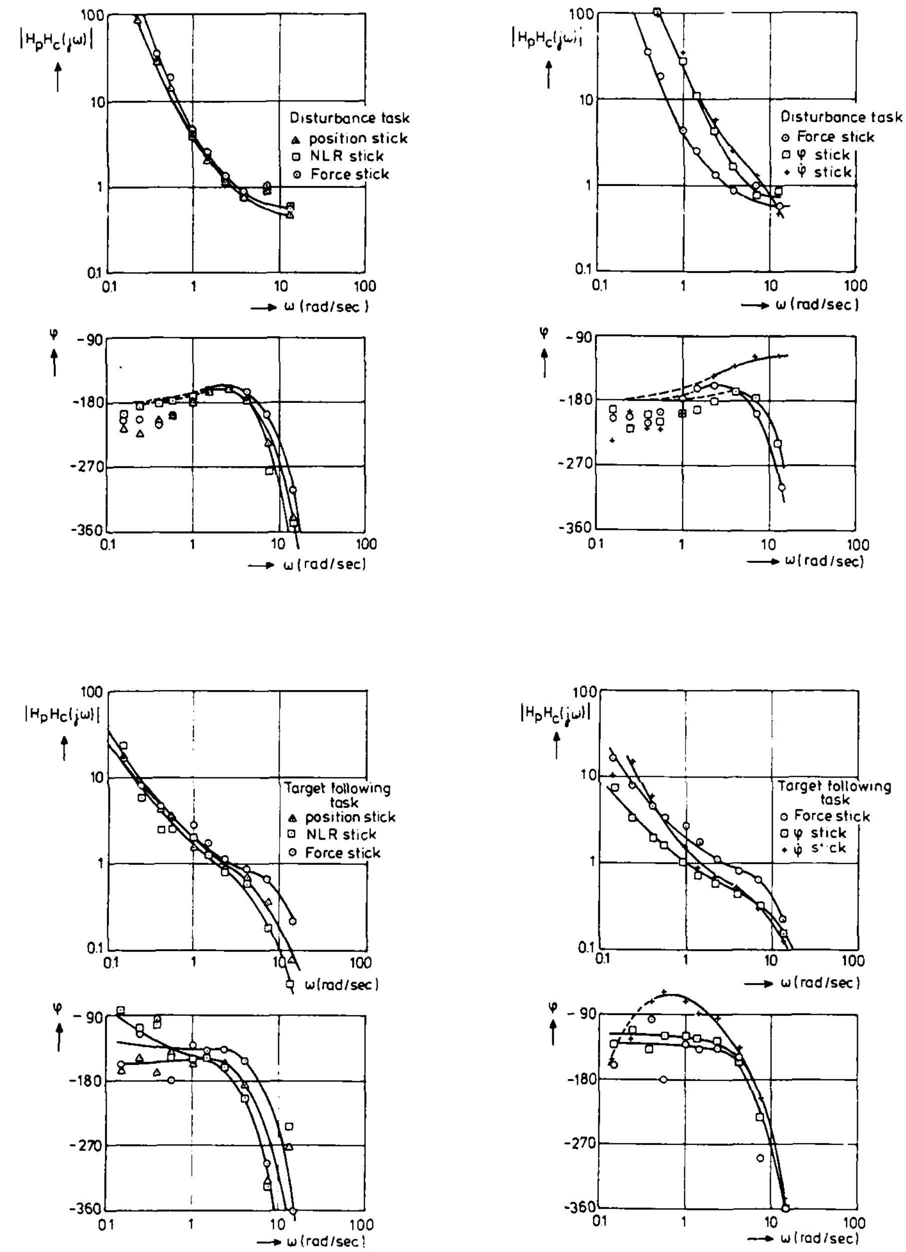

Fig. 13. Bode plots of the open loop describing functions $H_pH_c(j\omega)$ for the five side stick configurations and two tasks.

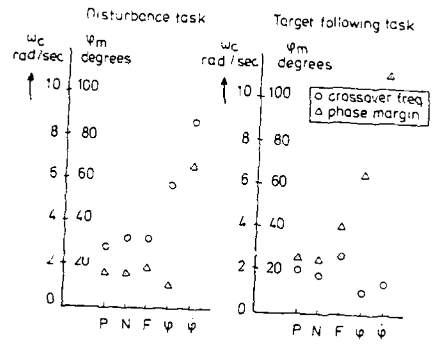

Fig. 14. Crossover frequency ω_c and phase margin ϕ_m of the open loop describing function $H_pH_c(j\omega)$.

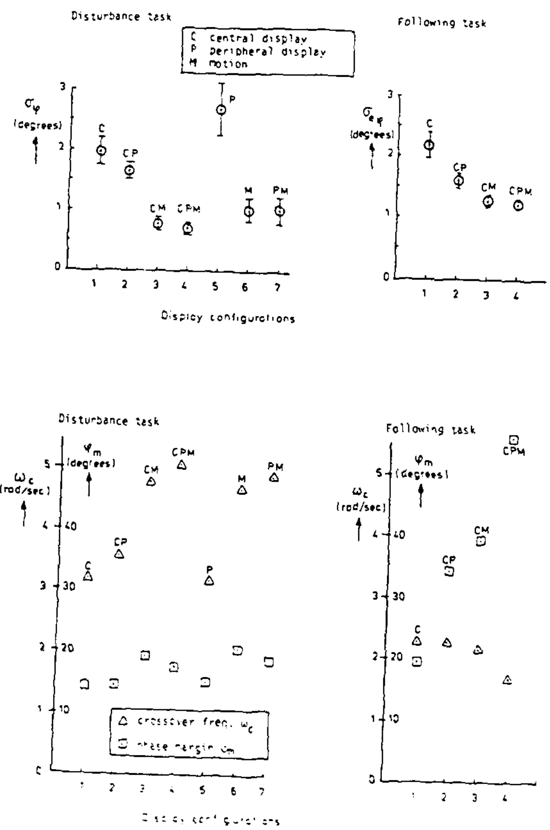

Fig. 15. The influence of cockpit motion and peripheral visual cues on tracking performance and crossover frequency and phase margin from Ref. 9.

The Use of Integrated Side-arm Controllers in Helicopters

by

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Summary

This paper reviews work conducted with integrated Side-Arm (Sidestick) controllers in a variable stability helicopter at the Flight Research Laboratory of the National Research Council of Canada. The investigations have covered an eight year period and involved the use of three different types of controller. The advantages and dis-advantages of integrated controllers are discussed and an "informed opinion" of their applicability is presented. Finally, data acquired during a succession of piloted experiments, indicating that Level 1 handling qualities are achievable with these types of controller, are summarised.

Symbols (Used in the Illustrations)

BARE	Direct drive from inceptor to actuator
I TRIM	Integral Trim on Pilot's Command, direct drive
RD+IT	Light Rate Damping Augmentation plus I TRIM
RC	Rate Command (Very high level of Rate Damping)
RCAH	Rate Command, Attitude Hold
ACAH	Attitude Command, Attitude Hold
RCHH	Rate Command, Heading Hold (Yaw Axis)
ACRH	Acceleration Command, Rate Hold (Yaw Axis)
LOW	Low Bandwidth (0.75 to 1.5 rad/sec)
MOD	Moderate Bandwidth (2.0 to 2.7 rad/sec)
HIGH	High Bandwidth (2.8 to 3.5 rad/sec)

Introduction

The aviation community has, over the past two decades, become more and more interested in the high technology cockpit, to the extent that exotic electronic displays are becoming commonplace, while the term "Glass Cockpit" has definitely entered the vocabulary of the industry. The same rapid advances in electronics and computer technology have permitted the augmentation or modification of aircraft responses to an unprecedented level, even to the automation of some of the functions traditionally assigned to the human pilot. Research conducted at the Flight research Laboratory (FRL) of the National Aeronautical Establishment (NAE, a Division of the National research Council of Canada) is contributing to both these aspects of modern aircraft design specifically as they apply to the helicopter. For the past eight years the Laboratory has been conducting piloted experiments into the use of integrated Side-Arm Controllers (SAC) using the Airborne Simulator (a highly modified fly-by-wire Bell 205-A1, illustrated in Figure 1 and fully described in Reference 1) as the primary research tool.

This paper will review the research which has been conducted using three types of SAC, these being Isometric Force Sensing, Limited Compliance Force Sensing and Large Deflection Position Sensing respectively. These controllers (Figures 2a, b and c) were all capable of providing outputs in four degrees of freedom as shown in Figure 3. Support structure for the controllers, incorporating arm rests were attached directly to a standard Bell 205 seat (Figure 4). The controllers were used both with primitive (open loop) and a variety of closed-loop active control systems.

A variety of controller configurations has been used, from the simplest in which the SAC simply replaced the conventional cyclic controller to the fully integrated four function application in which the SAC was the only inceptor of the pilot's commands. Fully integrated controllers have been installed for ambidextrous use also.

Justification

When the decision to initiate SAC research was taken, little was known about the practical application of these devices in helicopters. There did, however, appear to be considerable advantages to be gained from their use if it could be accomplished **without a significant degradation in handling qualities and if the prima facie dis-advantages in their use could be overcome.**

Advantages

Improved Pilot Efficiency

Since conventional helicopter controls require the use of all limbs, ancillary tasks must be performed on a stolen-time basis by abandoning a primary control, normally the collective lever. In some flight phases this can be done with impunity, at other times it is inappropriate if not dangerous and subsidiary tasks must be delayed. Integrating primary control functions onto a single device such that one arm is freed indefinitely for other uses has the potential to reduce workload and relieve stress in the cockpit. The provision of two controllers for ambidextrous use can free either hand for alternate duties, not only assisting the pilot, but also freeing the designer to produce ergonomically more attractive cockpits than is presently possible. This is, perhaps, the most compelling single argument for the use of integrated SAC, always assuming that vertical axis control would be the first function to be integrated with pitch and roll.

Additional Usable Cockpit Space

Upon the installation of SAC the volume previously swept by the cyclic stick is released for alternative use. Since this is centrally located and within easy reach and sight of the pilot, it must be considered a prime region. Additionally, existing areas not presently attractive because of visual obscuration by the pilot's arm and cyclic stick or because of inaccessibility to the left hand also become usefully available.

Simplified Control Grips

Current helicopters carry a plethora of ancillary controls on the primary control grips to accommodate the fact that the pilot may not always abandon a controller at will and must therefore have any essential secondary controllers placed so that they can be operated without removing the hands. This constraint detracts from the desireable practice of the functional and intuitive grouping of controls and displays. The restriction evaporates with SAC installations; in fact, the opposite approach is indicated since informal investigations show that there are difficulties in placing ancillary controls on a multi-function SAC in such a way that they can be operated without degrading primary control activity.

Reduced Fatigue and Improved Pilot Health

The rapid onset of fatigue compared with that experienced by fixed wing pilots and the prevalence of lower back medical problems amongst helicopter pilots are well recognised phenomena. Amongst the quoted contributory factors of the former is the inability of the pilot, when flying current machines, to make those body position changes useful in reducing muscle tension and easing discomfort. The latter stems largely from the 'helicopter crouch' a poorly supported, curved spine sitting posture frequently adopted by helicopter pilots as a necessity in handling the controls and which they have to maintain in a very vibratory environment. The upright seating and upper body support provided by the armrests implicit in SAC installations eliminates the hunched position and permits tension relieving body movements.

Reduced Inter-action with Active Control Systems

Experiences with high gain active control systems at the FRL has indicated the existence of a pernicious problem in the form of a relatively rare type of Pilot Induced Oscillation (PIO). This is not the classic PIO in which pilot-induced lag interacts with the vehicle dynamics to cause periodic closed-loop instability but is due to uncontrollable bio-mechanical-inertial feed-back. Aircraft motions feed back into the control loops via the seismic sensor formed by the pilots upper body, arm and cyclic stick, causing, under some conditions, outer loop instability. This can result in gross and rapidly divergent aircraft motions or can excite unusual aircraft structural modes, usually at frequencies higher than those associated with the classic PIO. These effects are still present with SAC, but are of much higher frequency still. Not only do the devices themselves have a higher natural frequency than the usual cyclic stick, but the armrests tend to force a node at the pilot's fore-arm. This effectively isolates the upper body from the feed-back system, reducing the effective seismic mass and further raising the system resonant frequency. Generally the frequency of oscillation with SAC is well above the pilot's bandwidth and the tendencies can be controlled by relatively simple conditioning of the SAC signals. To control the condition when using conventional controls it has been found necessary to simulate a stick with very high values of viscous damping and inertia, characteristics generally detrimental to the handling qualities of the machine.

Disadvantages

Manual Resolution

Typically in present helicopters, control throws are in the order of plus and minus 10 to 15 cm for the cyclic stick and 25 to 30 cm for the collective

lever; the human pilot is capable of making consistent changes in the position of such controls to within a few millimetres. Inputs of this level are frequently used in the stabilisation task, often as the open loop first response to external disturbances. The largest full scale displacement at mid hand position amongst the side-arm controllers evaluated is approximately 2.5 cm and therefore an input at the lowest possible resolution is a much larger proportion of the total control throw than is the case with traditional controllers. With isometric or low compliance force sensing devices yet more cues are lost, since the human being is far less adept at estimating the force he is applying than the skeletal position he is in. Moreover the body tends to wash out the tactile sensation from a sustained force causing a tendency to increase the applied force with time in the absence of other cues. Pilots appear to compensate for both the latter effect and the loss of good positional feed-back cues by using pulsed control strategies for very small inputs.

Controller/Controlled Element Relationship

In current unaugmented helicopters, there is a fixed relationship between the controller and the controlled element (actuator), from which the pilot gains a great deal of information. In the cyclic stick he has a direct analogue of the orientation of the thrust vector, essential information during some flight phases, while pedal position provides him with information regarding the ambient wind or his lateral velocity. From all controls he obtains an immediate indication of incipient control saturation, a very real threat to the helicopter pilot. This immediate information is irrevocably lost on conversion to SAC, but that may not be serious. It is most unlikely that SAC would ever be considered for a primitive machine, while once closed-loop or response command control systems are used the direct relationships cease to exist. Also, with well designed control systems some of the information may no longer prove to be essential[1].

Inter Axis Cross Talk (Cross Coupling)

All the side-arm controllers used at FRL have exhibited some degree of cross talk, the most common being pitch to vertical and vertical to pitch in the force sensing units and vertical to roll in the early models of the displacement controller. The characteristics in the force sensing devices were greatly reduced by a re-deign of the grip (Reference 3 and Figure 5) and by a reduction in ball size in association with modified grip geometry for the displacement controller. Both types of SAC have low level residual cross talk, but this is not obtrusive and does not produce any adverse commentary from evaluators.

Historical Summary

The various investigations conducted into SAC at the Flight Research Laboratory have generally been triggered by much larger programs initiated by other agencies. In late 1979 FRL was approached by the Sikorsky Aircraft Division of United Technologies with a request that it conduct a feasibility study into the operation of a four degrees of freedom, isometric, force-sensing SAC in the Airborne Simulator. A joint research project with Sikorsky was undertaken and completed in mid 1980, following a comprehensive development period and a systematic evaluation by test pilots from both FRL and the company. The results (Reference 2) were not published until some twelve months later due to a confidentiality agreement between FRL and Sikorsky.

Following this, a series of in-house experiments was conducted, inspired by research being conducted both at Boeing Vertol in Philadelphia and at NASA(Ames) in support of the US Army ADOCS (Advanced Digital Optical Control Systems) project. The FRL had a close but informal link with this project, a NAE pilot taking part in many of the early simulations (References 4 and 5). Observations made at these suggested that for investigations in low speed visual flight, ground simulation data should, where possible, be validated in the air. By 1985 this had given rise to the work published in Reference 6.

For the past two years FRL has been involved as a co-operative partner (its activities being supported and partially funded by the Canadian Department of Defence), in the US Army sponsored MIL-8501-A update project. This generated additional SAC research, since it was felt that specifications to which a future generation of military helicopters were to be designed should cater for the possible use of SAC. Detailed results of part of this work appear in Reference 10.

Finally, CAE Ltd of Montreal wished to develop a displacement SAC for helicopter use as an offshoot of their work on multi-axis inceptors for space vehicle applications. Another joint research project initiated a period of iterative development,

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[1] Flying attitude command systems in the Airborne Simulator, off level landing became a single input task. From a stable hover one simply had to lower the collective lever and as the aircraft made ground contact and rolled onto the slope the attitude loops made the required inputs to position the lift vector in the correct direction and by the correct amount.

with successive engineering models of a four-function displacement SAC being evaluated in the Airborne Simulator. While the development aspect of this program ended in late 1986, the final model remains available to FRL for further generic research. Data from this activity has been published in References 7 to 9.

The extended series of formal investigations was supplemented throughout by familiarisation and demonstration periods for a wide range of interested groups. SAC systems have been flown and evaluated by helicopter manufacturers (Sikorsky, Bell, Boeing, Hughes, MacDonald-Douglas and Westland Helicopters), NASA, the RAE, DFVLR, DND, US Army and US Navy. Whenever possible these sessions were used to acquire further HQR data and some of these, taken in a recent US Army (AEFA) and NASA(Ames) evaluation, are presented in this paper.

Summary of Experiments

It is always a problem when researching radically new technologies to determine the best course of investigation with the limited resources available. Each SAC experiment raised further questions, or indicated new facets for study. Despite this, SAC research at FRL has followed a logical path; the original feasibility study concentrated on applications in the primitive control system environment, while subsequent investigations progressed to the use of active control systems. Rate Command/Attitude Hold (RCAH) and Attitude Command/Attitude Hold (ACAH) systems have been flown in pitch and roll, Acceleration Command/Rate Hold (ACRH) and Rate Command/Heading Hold (RCHH) in yaw.

Discussion and Summary of Findings

Discussion

Pilot Acceptance. In discussing the results achieved in such a long program, generalities will be the rule, also, results based on Cooper-Harper ratings can never tell the entire story and in particular they do not address the issue of pilot acceptance. In verbal debriefings and informal discussions with evaluators, it has become apparent that there exists, amongst a small but not insignificant proportion of them, a tendency to reject SAC on emotional rather than technical grounds. This is by no means surprising when one considers that they are highly experienced pilots, heavily conditioned to conventional machines and that they generally received no more than two hours training on SAC prior to evaluation[2]. Despite this, such pilots would frequently assign Level 1 HQR to the systems even while expressing a dislike for or lack of comfort with them. This is considered significant and it is expected that the antipathy towards SAC would fade with increased exposure.

A Personal Note. This section represents a radical departure from tradition and from accepted practice for technical presentation in that it presents a personal view.

" Having been intimately involved in the Side-Arm Controller program at the NAE from the very start, having flown in all of the programs both as development pilot and evaluator and having created most of the control system software, I feel that I have a unique viewpoint on these systems. I feel also that this is justified as a counter-balance to some of the adverse comments that one hears. I acknowledge, nevertheless, that this is just one pilot's view.

I have now acquired over 250 hours of actual SAC flight time, have flown a similar amount as safety pilot observing others and have flown a number of ground based SAC simulations. Now, even in projects unrelated to SAC, I usually employ them for the development phase as a matter of preference. I find the improved comfort and the ability to interact with a computer system when actively flying to be great benefits, while I have no more consideration as to how or whether I should perform a required manoeuvre than I do with conventional controls.

SAC have now been experienced, briefly, by quite a large number of pilots, very few of whom have ever acquired more than a handful of hours in actual flight. Moreover, in the typical handling qualities experiment they will have been exposed to a range of control systems of varying response types and quality, good and bad; this in about the same number of flight hours the military typically allocates to cross train a pilot from one type to another. It is to be expected that they would come away from the experience with, at best, a certain ambivalence towards integrated controllers.

It is my unequivocal opinion that Integrated Side-Arm Controllers are a viable and rational approach to interfacing the pilot with his machine. In no way do they detract from his capability to control the aircraft, nor do they demand any unusual or excessive skill: Integrated Controllers do not reduce the usable normal flight envelope. A certain measure of pilot assistance is required, but no more than is currently considered necessary for future helicopters in their envisioned tasks and roles.

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[2] It has been found that two hours training or familiarisation is adequate for the great majority of pilots prior to evaluating SAC tasks, with a significant proportion signifying that they feel themselves to be sufficiently capable with the system to commence evaluation before the end of this period.

My experiences have led me to believe firmly that many of the misgivings felt about SAC are due to lack of experience. Overall workload does not, I feel, increase with well designed integrated controllers mated with well designed control systems, though it does seem to transfer between the axes. Many of the adverse comments heard regarding vertical control with Side-Arms stem not from intrinsic difficulties in the task, but rather because the workload in that channel is higher in proportion to that in the other axes than is the case with conventional inceptors. Evaluators, largely because of their training, tend to focus on difficulty rather than ease.

Finally, my comfort with and complete acceptance of fully integrated SAC are not recent phenomena, they have been with me sufficiently long that I cannot remember the early discomforts. This is the logical extension of the pattern of rapid pilot adaptation which we have observed many times over in the great majority of pilots, even those who have shown a marked bias against integrated controllers." (Morgan)

Summary

HQR Level

From all the experimental data gathered so far, one fact emerges consistently: it is possible to achieve Level 1 HQR using a fully integrated SAC with very little augmentation of the basic aircraft responses. This has been a repeatable observation in data provided by a wide variety of pilots using all three controller types in a wide range of tasks. This finding is illustrated in Figure 6 which summarises all available data for fully integrated configurations. While the unaugmented aircraft, with the SAC driving the actuators directly via a simple gain is shown as a borderline Level 2 vehicle, the addition of such a simple pilot assist as an integral or follow-up trim brings it to a high Level 2 while the further addition of a small amount of rate damping augmentation in pitch, roll and yaw makes the aircraft a definite Level 1 machine.

Level of Integration

If the level of controller integration is reduced by retaining the yaw pedals the results of Figure 7 obtain. In this case even the unaugmented but self trimming vehicle is firmly Level 1. In view of this observation there would appear to be no pressing argument for the use of levels of integration greater than this from a piloting point of view (though this does not preclude other considerations from making full integration an attractive proposition). Reverting to yaw control via the feet still achieves one of the main objectives of controller integration,it releases one of the arms for ancillary tasks yet it does not make as many demands on the pilot's neuromuscular control system as does the fully integrated configuration. This is an important step in the humanising of the helicopter cockpit.

Control System Sophistication

Automation of one or more of the stabilisation tasks normally carried out by the human pilot can have a very beneficial effect on overall vehicle handling qualities. This is illustrated in Figure 8, taken from Reference 6. Here a lightly rate damped aircraft in pitch roll and yaw was brought to an overall Level 1 by the implementation of either of two advanced control systems in the yaw axis only, Rate Command/Heading Hold (RCHH) or Acceleration Command/Rate Hold[3] (ACRH). This result was confirmed in later experiments, when the provision of RCAH and ACAH systems in pitch and roll produced good Level 1 HQR.

Control System Characteristics

One of the 8501 Update investigations was concerned with the effects of control system bandwidth on HQR for Rate Command,RCAH and ACAH systems in pitch and roll. Data was taken both with conventional controls and a displacement fully integrated SAC. Close examination of the results presented in Reference 10 and re-plotted as Figure 9 indicates that pilots were more tolerant of low bandwidth systems when using the SAC than when handling traditional controls. This observation may have been influenced by the method used to measure bandwidth (Computer generated frequency sweeps) and will be subject to further investigations.

Concluding Remarks

The Flight Research Laboratory now is the repository of some eight years of experience in the operation of a helicopter in all regimes of flight with fully integrated side-arm controllers in place of the conventional inceptors. This experience, together with informal investigations indicate that Integrated Side-Arm Controllers are a viable alternative to the traditional control levers and pedals for helicopter use and demand only low levels of vehicle response augmentation, to produce handling qualities equal to those achievable conventionally. They do not limit the pilot's ability to control his machine nor limit the normal flight envelope. It is

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[3] The detailed results of this experiment, showing approximately even preference for either RCHH or ACRH systems was quite different form a similar experiment conducted in ground based simulators which indicated very poor HQR for the ACRH system under all conditions.

acknowledged that there is still a great deal of work to be done in this area to make such devices acceptable to the helicopter community at large and it is the intention of the laboratory to continue with this research and to expand our understanding of these radically new inceptors.

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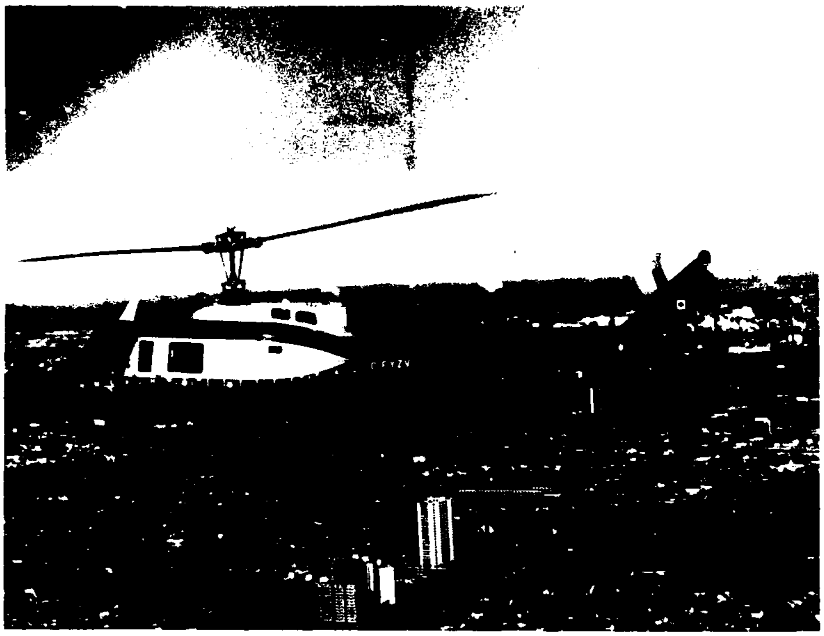
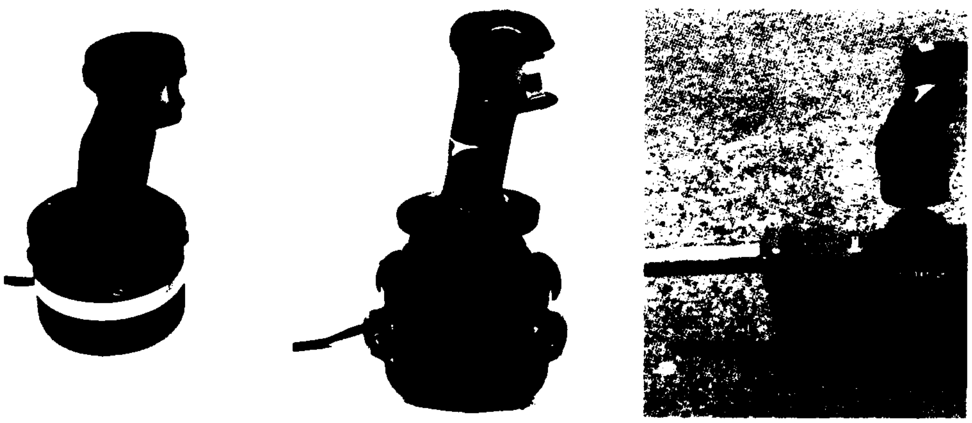


FIG. 1: NAE AIRBORNE SIMULATOR



(a) Isometric (b) Limited Compliance (c) Displacement

FIG. 2: THE SIDE ARM CONTROLLERS

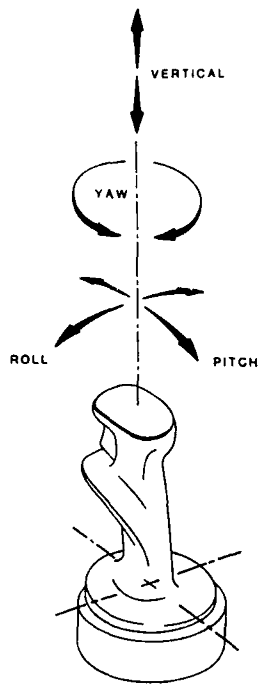


FIG. 3: CONTROLLER SENSING AXES

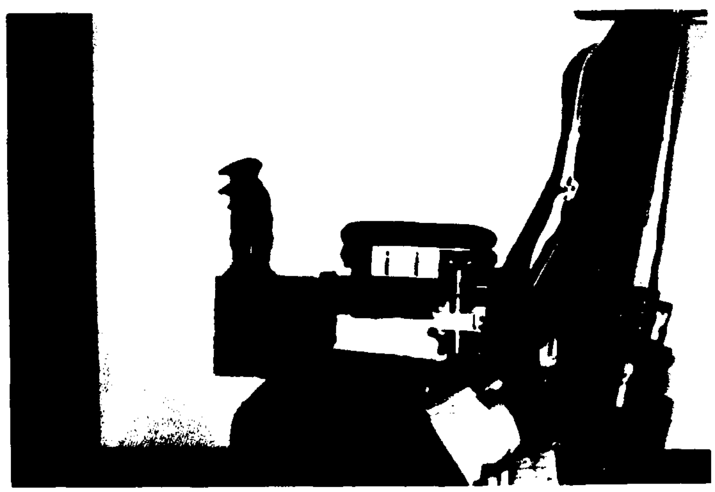


FIG. 4: BELL 205 SEAT WITH INTEGRATED SAC

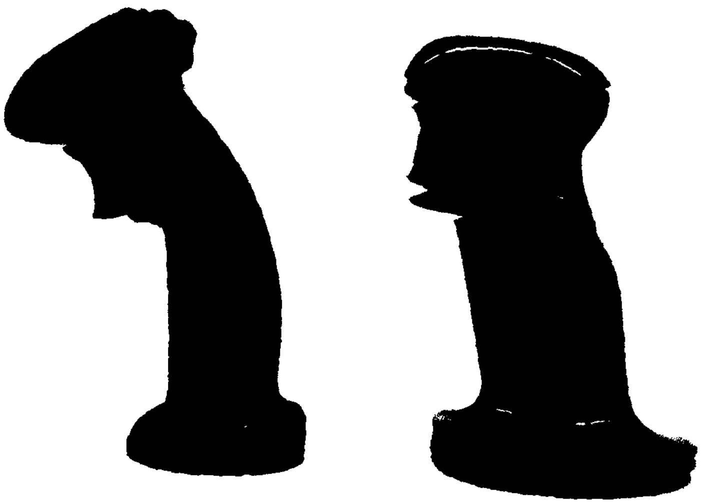


FIG. 5: MODIFIED HAND GRIP

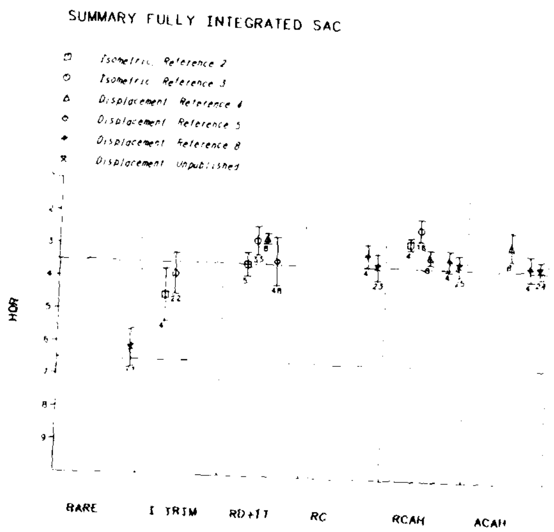


FIG. 6: SUMMARY OF ALL AVAILABLE DATA FOR FULLY INTEGRATED SIDE ARM CONTROLLERS

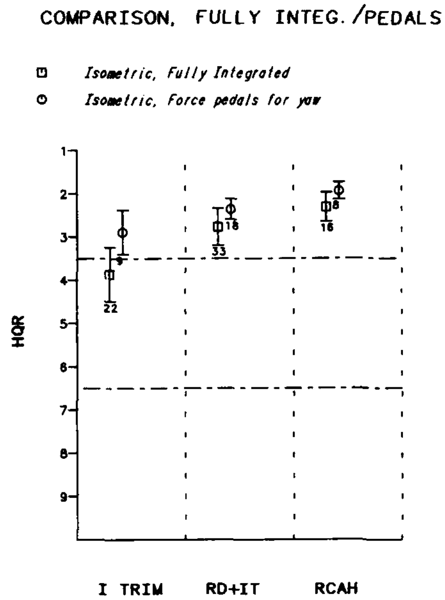


FIG. 7: COMPARISON OF FULLY AND PARTIALLY INTEGRATED CONFIGURATIONS

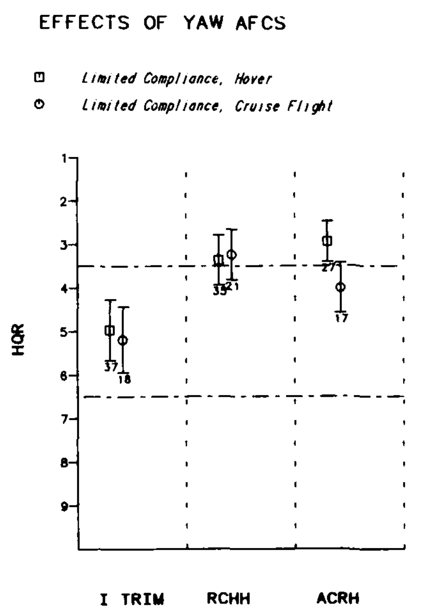


FIG. 8: EFFECTS OF CONTROL SYSTEM AUTOMATION

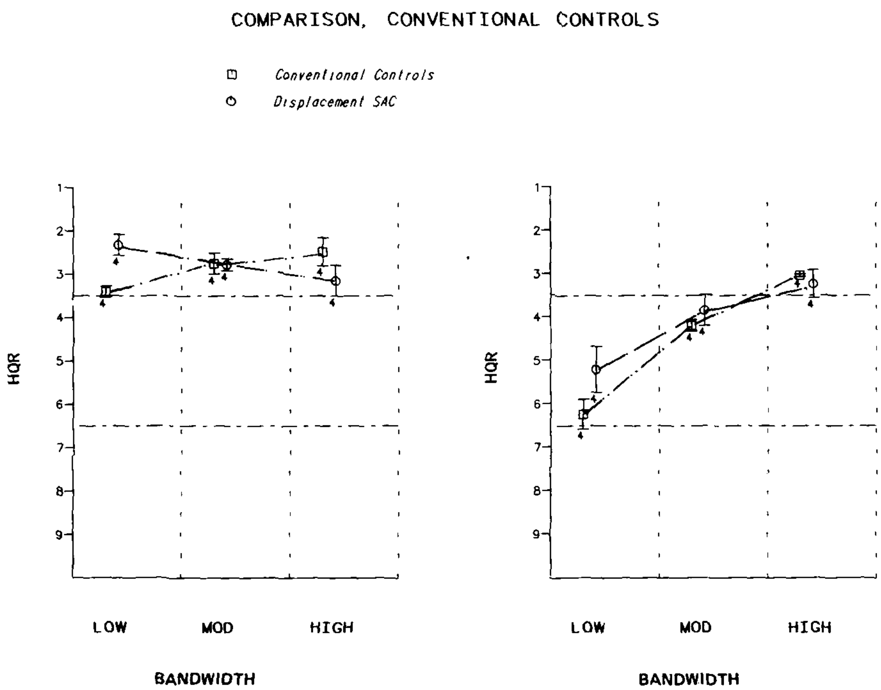


FIG. 9: ILLUSTRATION OF THE EFFECTS OF CONTROL SYSTEM BANDWIDTH ON CONVENTIONAL CONTROLS AND SIDE ARM CONTROLLERS

ADVANCED FLIGHT CONTROL SYSTEM FOR NAP-OF-THE-EARTH FLIGHT

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ABSTRACT

A digital/optical flight control system has been implemented on a UH-60 Black Hawk helicopter to determine flight control system requirements for Nap-of-the-Earth (NOE) flight. Small-displacement side-stick controllers with unique force trim positions were an integral part of the control system design. Controller configurations could be readily altered from a fully integrated four-axis side-stick controller to separated controller configurations including (3+1)Collective and (2+1+1). Control laws were implemented with a model following architecture that facilitates variations of control response characteristics.

The Automatic Flight Control System (AFCS) was designed to provide level 1 handling qualities and the Primary Flight Control System (PFCS) was implemented to achieve level 2 handling qualities. The interrelational effects of controller configuration and piloting task on handling qualities was investigated. Handling qualities were evaluated using precision hover and low-speed tasks typical of NOE flight as well as tasks performed at airspeeds from 80 to 120 knots. Piloted results are presented with recommendations for future systems utilizing small-displacement side-stick controllers in their design.

NOTATION

AATD - Aviation Applied Technology Directorate
ACC/AFCS - Advanced Control Concepts/Advanced Flight Control System
ADOCS - Advanced Digital Optical Control System
AFCS - Automatic Flight Control System
AGL - Above Ground Level
BUCS - Back-up Control System
DOCS - Digital/Optical Control System
FCP - Flight Control Processor
FCS - Flight Control System
HQRS - Handling Quality Ratings
IGE - In Ground Effect
LHX - Light Helicopter Experimental
MSSP - Mode Select Status Panel
NOE - Nap of the Earth
OGE - Out of Ground Effect
PCDU - Parameter Change and Display Unit
PFCS - Primary Flight Control System
PIO - Pilot Induced Oscillation
SCAT - Scout/Attack
SSC - Side-stick Controller
VMC - Visual Meteorological Conditions

INTRODUCTION

The Advanced Digital/Optical Control System (ADOCS) Demonstrator program was initiated in 1980 to develop the technologies required to implement an ADOCS on the next generation of scout/attack (SCAT) rotorcraft. Distinct technology elements of the ADOCS design include fiber optic links for communication between system elements, multi-axis side-stick controllers (SSC), and digital flight control laws developed specifically for the SCAT mission with emphasis on Nap-of-the-Earth (NOE) flight.

The primary objective of the ADOCS Program was to demonstrate feasibility and evaluate performance of a Digital/Optical Control System (DOCS). Program goals were to achieve Level 1 Handling Quality Ratings (HQRS)[1] for augmented flight, and Level 2 HQRS for flight without stability augmentation. More specifically, the DOCS was designed to provide unaugmented handling qualities equal to those of the production unaugmented mechanical flight control system (FCS), and augmented stability and control characteristics which demonstrate improved handling qualities and reduced pilot workload for the SCAT mission tasks.

Flight testing of the "Light Hawk", a modified JUH-60A (Fig. 1), began on November 7, 1985 with the first fly-by-light maneuvering performed using the PFCS. The flight test program was carried out in two phases from Nov. '85 to the present. The first phase was directed toward development of the Primary Flight Control System (PFCS); the flight critical link between the pilot and the swashplate actuators. Subsequent testing, which started in January 1986, concentrated on optimization of the Automatic Flight Control System (AFCS) which included refinement of both the stabilization loops and the command/response characteristics based on flight evaluation results. This paper briefly describes various system components comprising the ADOCS and documents the results of piloted handling qualities flight evaluations of the system.

SYSTEM DESCRIPTION

Elements of the ADOCS design most influential in affecting the aircraft handling qualities are summarized in the following paragraphs. Additional details of the system design including system hardware and testing can be found in Ref. 2.

SIDE-STICK CONTROLLERS (SSC)

Three side-stick controllers were installed in the ADOCS Demonstrator aircraft as indicated in Fig. 2. A 4-axis controller is located on the right-hand side of the DOCS pilot seat, while a single-axis collective controller is provided on the left-hand side. The DOCS pilot station is also equipped with small-displacement force pedals. A second 4-axis controller is installed on the right-hand side of the DOCS observer station (located in the rear cabin area) solely for evaluating the control laws for transfer of control between the DOCS pilot and copilot (and vice-versa).

Three controller configurations were evaluated on the Demonstrator as shown in Fig. 3. Initial simulation results obtained during the ACC/AFCS program[3] recommended separation of the collective controller for high workload tasks. Isolation of the collective controller, as in both the (3+1)Collective and (2+1+1) configurations, resulted in improved pilot ratings compared to the (4+0) configuration.

Force/displacement characteristics of the ADOCS 4-axis side-stick controller are presented in Table 1. These characteristics were determined through a series of piloted simulations reported in Ref. 3. Characteristics of the flight hardware met recommended values with the exception of the breakout forces which could not be reduced to desired levels because of mechanical limitations of the transducers. The friction levels in the transducers were reduced to levels which did not degrade handling qualities. Pilot comments obtained during evaluation flights indicate that the force/displacement characteristics of the ADOCS controllers were acceptable for the tasks performed with the possible exception of the yaw axis. Some pilots felt that the yaw axis force/displacement gradient was too high for NOE tasks.

PRIMARY FLIGHT CONTROL SYSTEM (PFCS)

The PFCS (Fig. 4) provides the only link between the DOCS pilot and the control actuators and is designed as a flight critical element of the FCS. A complete description of each PFCS element is provided in Ref. 4. The following is a description of those PFCS elements which were modified during flight testing including: control filtering, dynamic shaping, and automatic trim follow-up.

<u>Digital notch filters</u> were provided in the PFCS in all axes to eliminate the feedback of structural vibrations into the control paths. Flight test data were analyzed to select the filter frequency requirements. Second order algorithms were selected for all notch filters.

<u>Dynamic shaping</u> (Fig. 5) was included in the PFCS control path to provide control quickening because the basic response characteristics of the unaugmented UH-60A are sluggish, particularly in the pitch and yaw axes. The dynamic shaping was designed to alter the short period basic aircraft response by effectively canceling inherent short period roots and substituting poles which provide a more desirable response characteristic. Basic response characteristics of the UH-60 in the roll and vertical axes were judged acceptable without modification due to the inherent damping of the aircraft.

Automatic trim follow-up algorithms are provided in each axis to eliminate requirements for the pilot to hold steady-state control trim forces. As shown in Fig. 5, a non-linear digital integration path is used to store trim requirements. Actuator positions are demixed to provide equivalent cockpit control displacement used as the input to the trimming algorithm. In this manner, the most current rotor control position is used in the trimming loop. Automatic trimming is disabled by logic when the controller is returned to its unique neutral position to eliminate any long term drift which may occur.

AUTOMATIC FLIGHT CONTROL SYSTEM (AFCS)

Control Law Architecture

The ADOCS control laws employ a modified explicit model following concept[5] as shown in Fig. 6. The PFCS feed-forward path transfer function D(s)/P(s) is intended to cancel aircraft inherent short period modes while substituting roots of a desired response. Ideally, even without an AFCS, the aircraft response to a pilot command input would reflect the dynamics in D(s) and not in P(s). The AFCS command model generates predicted aircraft states based on the dynamics contained in D(s). State errors (the difference between the expected state and the sensed state) are formed and passed through appropriate stabilization gains. Any state errors existing in the AFCS are due to inexact cancellation of the aircraft dynamics in the PFCS and external inputs such as gust upsets. The total AFCS command is passed through a port limit into the PFCS. Since the model following architecture provides a cancellation of closed loop aircraft dynamics, feedback design can be performed independently of feed-forward design, thus greatly reducing the optimization task.

Several issues as reported by Chen[6] have not been included in the above simplified presentation of the model following concept. Significant delay inducing components between the rotor command and the sensed aircraft states need to be considered in the analysis. These components include: DOCS driver actuators, UH-60 upper boost actuators, aircraft rotor dynamics, and sensor dynamics. Model following theory would include these dynamic elements as part of the aircraft model [P(s)]. However, analytical methods result in a PFCS command model which has an impractical amount of lead compensation because of noise resulting from high-order derivative terms. For this reason, these components have been excluded from the aircraft model, and accounted for by placing their approximate transfer function in the AFCS command path. A simplified block diagram of the control law implemented in the yaw axis is provided in Fig. 7. The AFCS state commands are effectively delayed to provide good matching between commanded and sensed aircraft states.

AFCS Modes of Operation

The Mode Select Status Panel (MSSP) (Fig. 8) provides the pilot with the capability of selecting various AFCS modes in flight. Selectable modes of operation include: Heading Hold (HDG), Barometric Altitude Hold (BARO), Radar Altitude Hold (RAD), Velocity Stabilization (VELSTAB), and Hover Assist (HVR). The "basic" mode of operation of the AFCS (referred to as the "core AFCS") results when all selectable modes are disengaged. Core AFCS functions are outlined in Table 2. For low speed operations, the core AFCS provides an attitude command/attitude stabilization (AT/AT) system in pitch and roll, an acceleration command/rate stabilization (AC/RA) system in yaw, and an acceleration command system in the vertical axis which contains no stabilization signals. In forward flight, the core AFCS provides a pitch attitude/airspeed hold (AT/AS) system, a roll rate/roll attitude (RA/AT) system, an AC/RA system in yaw, and an acceleration command system in vertical. Turn coordination is also provided in the "core" AFCS.

Selectable AFCS mode functions are defined in Table 3. Pilot comments indicate that the Heading Hold feature should be included as part of the core system since this feature tended to reduce pilot workload significantly for most tasks.

CONDUCT OF TEST

PROGRAM SCHEDULE

Test activities accomplished on the ADOCS Demonstrator aircraft from April 1985 to date are shown in Fig. 9. Integration of the DOCS on the UH-60A aircraft was validated before actual flight testing using the Boeing Vertol simulation facility. The aircraft was placed adjacent to the simulation lab. Flight characteristics of the basic UH-60A were represented with a six degree of freedom, non-linear total force/moment math model programmed on a Perkin Elmer Multi-processor computer used for real-time piloted simulation. The entire PFCS comprising side-stick controllers, optical transducers and signal paths, digital FCPs, DOCS actuators and other subsystems were operated closed loop on the aircraft for pilot in-the-loop validation testing. The simulator camera/terrain board system provided visual cues to the pilot via four television monitors mounted directly in front of the UH-60 cockpit windows. Thorough testing of all PFCS hardware/software interfaces and control logic was accomplished during this simulation task.

Following hardware-in-the-loop simulation, the aircraft was transferred to the Wilmington Flight Test Center where a five week period of ground testing was conducted prior to first flight. Because of the major modifications made to the UH-60A, both the DOCS and production systems were ground tested before flight releases were granted. Flight testing of the ADOCS aircraft began on October 23, 1985. First flights were conducted to insure production UH-60 system integrity and to confirm that the newly installed DOCS did not interfere with normal Back-up Control System (BUCS) operation.

During these initial tests, the DOCS was powered, but was mechanically disconnected from the UH-60 upper-boost actuators, i.e. the DOCS could be flown open-loop. These flights were used to evaluate sensor performance and interfaces by monitoring internal flight control processor (FCP) parameters.

The first closed-loop DOCS flight took place on November 7,1985. This flight was the first of many which were used to evaluate and develop the PFCS. Evaluation of the PFCS included testing of the DOCS Monitor (safety system) performance, aircraft response and pilot recovering from simulated AFCS failures, and evaluation of unaugmented handling qualities.

As the PFCS evaluation phase was nearing completion and unaugmented design objectives were being met, AFCS testing began. Initial AFCS evaluations included reviewing the system's digital effects on aircraft stability while optimizing feedback paths to provide desired levels of gust rejection and damping. With the stability loops defined, command model response characteristics were optimized to provide the pilot with desirable responses throughout the flight envelope. Selectable modes were also optimized and evaluated in this phase. Finally, NOE evaluations were conducted as well as air-to-air tracking and air-to-ground target acquisition tasks.

DATA COLLECTION

In addition to numerous data parameters monitored in real-time and recorded in-flight, pilot Cooper-Harper ratings and supporting pilot comments were obtained to evaluate the DOCS handling qualities. Averaged data presented herein consist of combined ratings from all evaluation test pilots when possible.

TASK DESCRIPTION

The evaluation tasks selected specifically to evaluate PFCS handling qualities are described below. Typically, Category B and C tasks[7] were performed for PFCS evaluation as they were felt most typical of degraded mode operation. Tasks used to evaluate the handling qualities with the AFCS operating were based on the proposed handling qualities specification - ADS-33[8] which includes more aggressive and precise maneuvers typical of NOE flight. PFCS evaluation tasks demonstrated "get home" capability in the event of multiple AFCS system failures. Tasks included: mild turns, climbs, descents, traffic pattern maneuvers, low-speed flight, and landings. AFCS tasks were designed to examine all facets of NOE flight and put more emphasis on precise maneuvering. Low-speed tasks performed in the evaluation of the AFCS included: lateral jink, accel/decel, slalom, hover turn, bob-up/down, precision hover, and takeoff/landing. Tasks performed at higher speeds included: roller coaster, high angle turns, approach to hover, and simulated autorotation. A detailed description of the evaluation tasks performed during these evaluations are included in Refs. 4 and 9.

PILOTED EVALUATION OF THE PFCS

Modification of PFCS system parameters and algorithms was performed during piloted testing to obtain Level 2 handling qualities and meet design objectives. Final results of the PFCS handling qualities evaluation are summarized in this section with a discussion of the results organized as follows:

- Requirements for automatic trim follow-up and control shaping
- Notch filtering for elimination of pilot/airframe coupling
- Side-stick controller configuration effects
- Comparison of DOCS and BUCS

AUTOMATIC TRIM FOLLOW-UP RATES

Control trim follow-up rates were increased in all axes during flight test optimization of the PFCS. Both the maximum integration rate size and the trim lag time constant were altered to increase the effective trim follow-up rate. The need for reducing trim forces at a faster rate was attributed to the increased stability of the actual aircraft compared to the simulator. The stability level of the unaugmented UH-60A math model in the simulator was perceived to be lower than the actual aircraft. This occurred because of the limited visual field-of-view and weak motion cues particularly when performing large excursion maneuvers from one trim flight condition to another. Thus, normal pilot control techniques tended to be less aggressive in the simulator resulting in slower automatic trim follow-up rates.

DYNAMIC SHAPING

Dynamic shaping, consisting of a lead-lag shaping network, was provided to increase pilot perceived bandwidth in both the longitudinal and directional axes. Significant changes to this shaping occurred during flight testing because of the simulator limitations previously stated. Fig. 10 presents the frequency response of three longitudinal axis lead-lag filters evaluated in flight test. As shown, simulation studies resulted in a filter design which provided the least amount of phase advance. This shaping when evaluated in flight test resulted in pilot complaints of response sluggishness. When the lead-lag was modified to provide a maximum of 35 degrees advance instead of 10 degrees, the pitch axis was judged too snappy and responsive causing a tendency to over-control in pitch. The final configuration selected provides 15 degrees phase advance and is actually the closest to the analytically predicted requirements previously described under system description. The final configuration succeeded in

minimizing the high frequency control inputs in the pitch axis and provided enough quickening to effectively reduce pilot workload. Similar results were obtained in the directional axis. Flight test results confirmed that no shaping in either the lateral or vertical axes was required to achieve Level 2 handling qualities with the PFCS.

PILOT/AIRFRAME COUPLING

Under certain flight maneuvers when constant SSC force inputs were required and aircraft structural vibration levels were high, a bio-mechanical feedback through the pilot's arm and into the control paths resulted. This condition most frequently occurred during forward flight climbs or descents. The pilot, while holding a steady collective command, experienced a high level of cockpit vibration at 6.5 hz (Fig. 11) which fed directly through the pilots arm into the SSC. Removal of the control force eliminated the vibration by effectively opening the structural feedback loop. A digital notch filter was designed and implemented in the collective control command path to essentially attenuate all 6.5 hz control inputs. Similar notch filters were included in all axes to eliminate any Pilot Induced Oscillation (PIO) tendencies. Since the addition of these notch filters, no PIO tendencies have been noted.

SIDE-STICK CONTROLLER CONFIGURATION EFFECTS

Initial flight test evaluation of the PFCS was performed using the integrated four-axis controller configuration, i.e. (4+0). With this configuration, pilots found it difficult to isolate problem areas because of inherent controller induced coupling effects. The use of separated controls (i.e. the (2+1+1) and (3+1)Collective configurations) allowed pilots to concentrate on responses axis by axis. In this manner, single-axis responses as well as automatic-trim rate could be optimized before multi-axis maneuvers were evaluated. Following the evaluation of the PFCS with the (2+1+1) controller configuration, testing of the PFCS with the (3+1)Collective configuration was conducted. The majority of flight testing was devoted to this configuration. Finally, after successful integration of the three control (pitch, roll, and yaw) on the SSC was completed, attention was again focused on evaluation of the four-axis configuration.

Average pilot ratings for the three side-stick controller configurations evaluated during PFCS optimization are presented on Fig. 12. In general, separated controller configurations yielded improved pilot ratings compared to the four-axis configuration. The largest benefit indicated, and supported by pilot comments, resulted from the separation of the power (collective) control. Removal of collective control from the right-hand SSC allowed pilots to set power at a desired setting and concentrate on controlling the other axes.

When the collective control was implemented on the right-hand SSC (i.e. (4+0) configuration), control inputs in pitch, roll or yaw tended to couple into the vertical axis resulting in a significant increase in pilot workload. This added workload was most noticeable for precision tasks performed near the ground. Pilot performance during liftoff and landing was degraded significantly when performed with the (4+0) configuration. Fig. 12 shows that ratings for these two tasks were degraded by two pilot rating points compared to either the (3+1) or (2+1+1) configurations. For less demanding tasks, pilot ratings with the (4+0) configuration were typically degraded by approximately one HQR point compared to the (3+1)Collective configuration.

Best pilot ratings were achieved with the (2+1+1) controller configuration. Evaluations of the (2+1+1) configuration (performed briefly during initial PFCS testing) indicate the added benefit of fully separated collective and directional controls for most tasks. Level 1 ratings were obtained for multi-axis turning tasks with the (2+1+1) configuration without stability augmentation. In addition, Level 1 pilot ratings were also obtained for the hover and taxi tasks.

DOCS-BUCS COMPARISON

Handling quality comparisons were performed between the DOCS PFCS and the UH-60 mechanical controls (BUCS) to assess how well design objectives of the PFCS were being met. Evaluations by the BUCS pilot were performed with both the production SAS and force-feel systems selected off.

A comparison between the average pilot rating data for the (3+1)Collective configuration and the unaugmented BUCS system is presented in Fig. 13. As shown, comparable pilot ratings were obtained for both configurations. Pilot comments indicate that some tasks, specifically the up-and-away turns and approach to hover tasks were performed better with the DOCS. High workload tasks, such as landings and takeoffs were performed more deliberately with the DOCS. Much of this cautiousness was attributed to pilot learning and/or experience. It should be noted that numerous evaluation pilots successfully performed hovering and landing tasks in an unaugmented state during the second hour of their DOCS flight evaluation.

PILOTED EVALUATION OF THE AFCS

STABILITY AND COMMAND CHARACTERISTICS

By applying both analytical techniques and in-flight test optimization, the ADOCS control laws achieved an excellent level of stability in all axes. Table 4 presents a summary of system bandwidth and stability margins as predicted by a system model which

includes a 6-DOF aircraft model. Data presented in Table 4 are for the hover flight condition. The system parameters presented in this table reflect the closed loop response of the aircraft to external inputs as opposed to pilot commands which pass through the ADOCS command model.

The command characteristics of each axis are presented in Table 5. System characteristics have been selected to be acceptable for all tasks. Both the stability and command response characteristics will be verified by in-flight frequency response testing[10] scheduled to be conducted later this year.

Attitude Command Systems

Many hours of piloted simulation were utilized during the ACC/AFCS program[3] to optimize the pitch and roll attitude command systems for low-speed NOE tasks. During flight test optimization, a modification to the desired response characteristics of the pitch/roll command model was required. Initially, both the pitch and roll command models included very low trim follow-up gains. These gains were increased significantly during flight testing changing only the low-frequency portion of the desired response definition. It was critical to quickly minimize steady-state forces being held by the pilot. The frequency response of the pitch axis AT/AT command model is indicated in Fig. 14 for both the initial and current definitions. The overall sensitivity and response shape (frequency and damping) of the short period response did not change significantly from the results of previous ACC/AFCS simulation efforts.

VERTICAL AXIS RESPONSE CHARACTERISTICS

"Core" AFCS

The "core" vertical control laws provided a normal acceleration proportional to pilot's force input. The response is very similar to the response with only the PFCS operating. The acceleration-type response enabled the pilot to set engine power at a desired value while eliminating any requirement to hold constant forces. However, precise control of aircraft rates of climb/descent required much learning and concentration. Pilot comments indicate that there was an exceptionally high amount of compensation required to control the vertical axis. As such, the performance of almost all low-altitude tasks was degraded because of the high pilot workload in the vertical axis. It should be noted that overall control of the vertical axis with the "core" system was accomplished with an unacceptably high amount of attention paid to the engine torque indicators in the cockpit. Pilot comments indicate that this is primarily due to the lack of tactile feedback provided by a collective force controller combined with the long lag associated with the aircraft's vertical response characteristics.

Altitude Hold

Both radar and barometric altitude hold systems are included in the ADOCS demonstrator aircraft. RADALT can be selected if altitude is less than 1000 ft AGL. With either system selected, vertical control laws are configured to provide a rate-of-climb command system. The vertical rate command response in conjunction with the long-term altitude hold feature dramatically reduced pilot workload for many evaluation tasks. However, because of complementary filtering performed on the radar altitude signal, RADALT did not provide as tight an altitude hold as desired during aggressive maneuvering in other axes. For example, during a 20 deg nose up deceleration through the translational lift region, altitude deviations of up to 15 ft were recorded. This system characteristic requires further analysis and modifications to meet SCAT mission requirements.

YAW AXIS RESPONSE CHARACTERISTICS

During testing to optimize yaw rate response in hover with heading hold engaged, a compromise was necessary between the time constant of the desired rate response and the deceleration response of the aircraft to lock onto a heading. That is, pilots desired a rapid rise time to start a yaw maneuver, but preferred a slower rise time to stop at a new heading reference. Typical pilot technique for yaw control with the SSC involved the smooth application of control forces followed by a rapid release. In order to handle this non-linear control requirement, the yaw axis derivative rate limit (DRL) parameters were adjusted to soften accelerations jerks for rapid release of control forces. The DRL did not affect yaw response for normal modulation of control input forces which resulted in crisp and precise heading changes.

PILOT RATINGS

Handling quality comparisons were performed between the DOCS AFCS and the UH-60 mechanical controls (referred to as BUCS) to assess how well design objectives were met. Evaluations on BUCS were performed with both the production SAS and force feel systems selected on. Pilot rating data presented consist of averaged ratings for each pilot. All data presented were obtained with the (3+1)Collective SSC configuration.

An assessment of task performance with both the ADOCS and UH-60 control system was performed by the Boeing evaluation pilot. A comparison of pilot ratings for each control system configuration is given in Fig. 15 for low-speed tasks and in Fig. 16 for forward flight tasks. AFCS mode status for ADOCS evaluations are noted on each figure. A discussion of pilot rating data including pilot comments is given below.

Low-Speed Evaluation Tasks

Pilot ratings with ADOCS were on the average slightly improved over ratings obtained with the BUCS for most of the low-speed tasks performed (Fig. 15). Level 1 ratings were not obtained for either control system for the hover about a point and dash/quickstop tasks. The hover about a point task required continuous pilot control activity in all axes and average pilot ratings of 4.0 were given for this high workload task. Ratings for the dash/quickstop varied from CHR 3 to CHR 5 depending on how aggressively the task was performed. Large commanded pitch rates and attitudes caused control deficiencies in the vertical axis to become more evident. Higher longitudinal SSC forces required to perform an aggressive accel/quickstop maneuver also produced a porpoise or PIO tendency in pitch.

For certain precision low-speed maneuvers including the hover turn, slalom, rearward flight, bob-up, and lateral jink, pilot performance was noticeably better with the ADOCS than the standard UH-60 system. Pilot comments indicate that the small-displacement SSC improved their performance of these tasks, especially if vertical axis control workload was minimal.

Forward Flight Evaluation Tasks

For all tasks except autorotation, Level 1 HQRS were obtained with the ADOCS (Fig. 16). The DOCS lateral axis controllability was judged superior to existing rotorcraft. The box pattern, a precise lateral/direction task, was performed easily. Sixty degree bank turns were made with no apparent overshoot using roll rates in excess of 40 deg/sec. The pilot commented on "feeling in control" and "very comfortable" while doing these tasks. Evaluation of the BUCS resulted in Level 1 ratings for all tasks except the 60 deg bank turn maneuver. For this task, lateral controllability was judged deficient when compared to the ADOCS. Autorotation, as expected from the PFCS evaluation, was more easily performed with the BUCS large displacement collective controller. Based on this task, as well as low-speed altitude/thrust control tasks, a medium displacement collective controller to provide improved tactile feedback to the pilot in the vertical axis is recommended.

SUMMARY

A fly-by-light Black Hawk has demonstrated state-of-the-art flight control technologies since November 1985. Development of a PFCS and integrated multi-axis side-stick controllers was successfully accomplished achieving Level 2 handling qualities. An AFCS was designed which, for most SCAT mission tasks, yielded reduced pilot workload and Level 1 handling qualities. Major findings resulting from flight test evaluation of the DOCS are summarized as follows:

1. An attitude command system in the pitch and roll axes resulted in level 1 handling qualities for low-speed NOE flight.

2. Higher trim follow-up gains in both the pitch and roll attitude command systems were required to more quickly trim out steady state forces and achieve level 1 handling qualities.

3. Non-linear shaping to obtain desired control sensitivities for small precise maneuvering and to minimize control forces during large maneuvers is necessary for pilot acceptance of force-type controllers. However, it was found that for some conditions, large sensitivity changes produced by the non-linear shaping causes pilot induced oscillations.

4. Heading Hold was found to dramatically reduce pilot workload during near-ground operation.

5. Hover Assist, though it tended to drift as a function of the Doppler ground-speed sensor, was found to decrease pilot workload for the precision hover task.

6. Phase delays introduced by all system components, including digital effects due to asynchronous operation of processors, must be accounted for in predicting system gain requirements and system performance.

7. A unique-trim force vertical controller degraded pilot performance in high workload situations where the pilot requires a continual cross check of torque in the cockpit (i.e. power setting and control position). Based on these results, a medium-displacement collective controller should be evaluated and compared to unique trim force controllers with improved control laws and/or displays.

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Figure 1. ADOCS Demonstrator Aircraft.

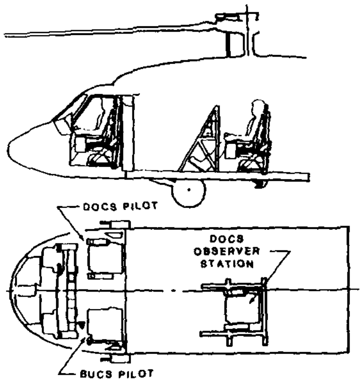

Figure 2. SSC Locations in ADOCS Demonstrator.

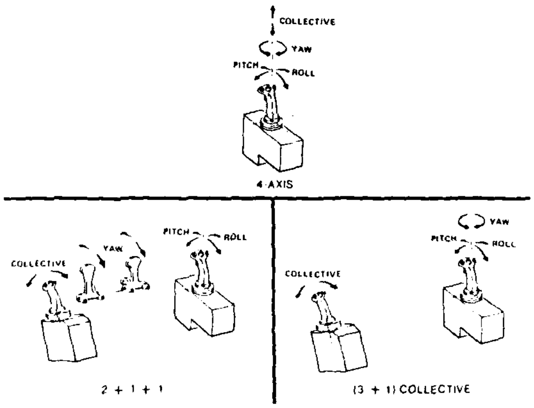

Figure 3. ADOCS Controller Configurations.

AXIS	DISPLACEMENT	MAX. FORCE	STIFFNESS
LONGITUDINAL	± 8.8 DEG	18.4 LB	2.09 LB/DEG
LATERAL	± 8.8 DEG	14.7 LB	1.67 LB/DEG
DIRECTIONAL	± 7.5 DEG	37.5 IN-LB	5 IN-LB/DEG
VERTICAL	± 0.166 IN	15.77 LB (UP) 14.11 LB (DN)	95 LB/IN (UP) 85 LB/IN (DN)

Table 1. ADOCS 4-Axis SSC Force/Displacement Characteristics.

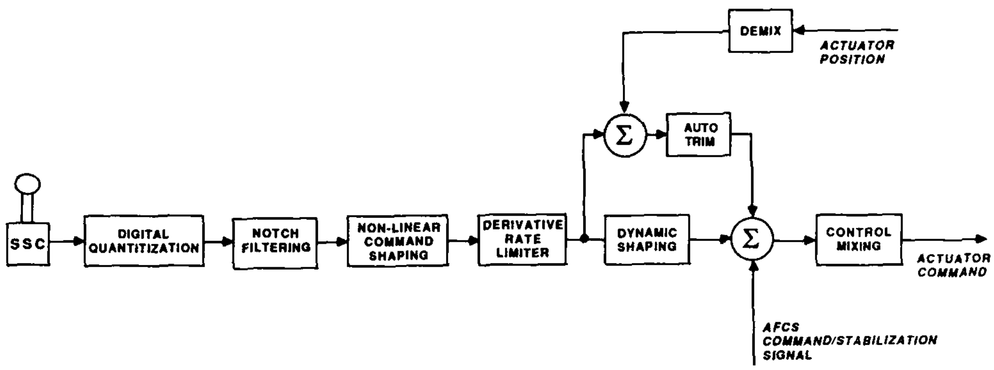

Figure 4. Elements of ADOCS Primary Flight Control System.

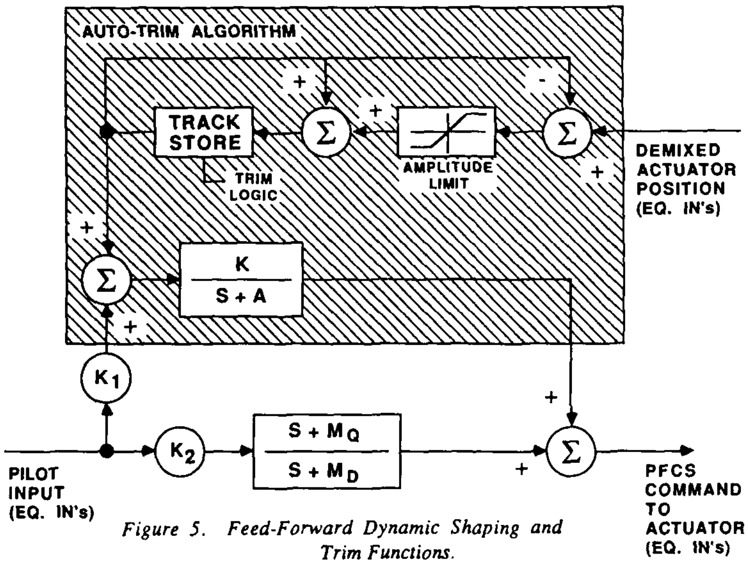

Figure 5. Feed-Forward Dynamic Shaping and Trim Functions.

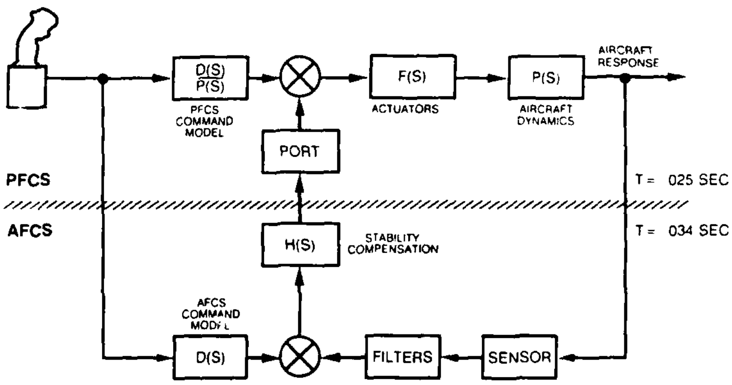

Figure 6. ADOCS Model Following Concept.

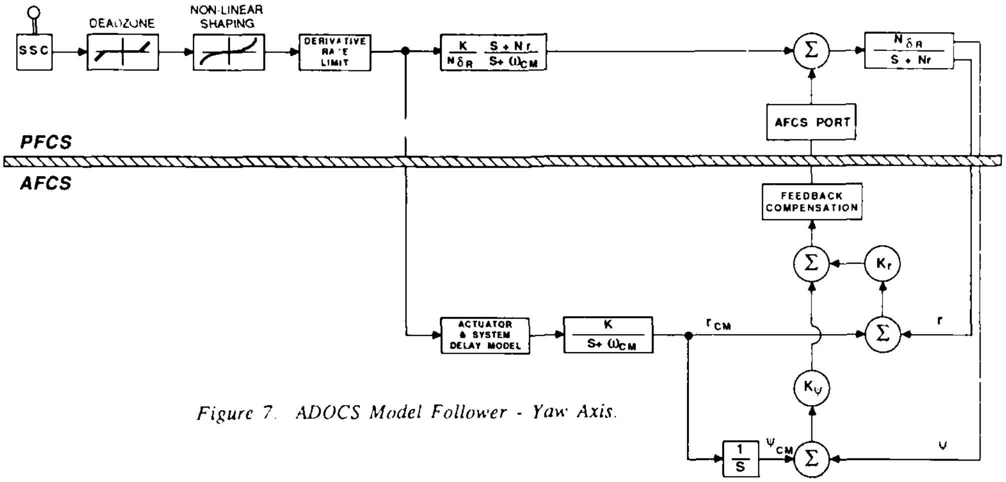

Figure 7. ADOCS Model Follower - Yaw Axis.

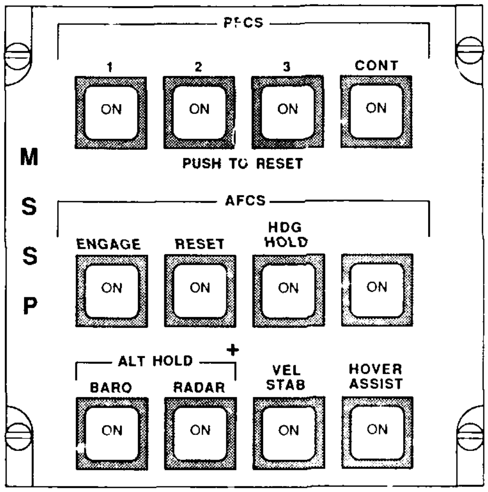

Figure 8. AFCS Mode Select Status Panel

AXIS	HOVER/LOW SPEED		FORWARD FLIGHT	
	COMMAND	STABILITY	COMMAND	STABILITY
LONGITUDINAL	PITCH ATTITUDE	PITCH ATTITUDE	PITCH ATTITUDE	AIRSPEED HOLD
LATERAL	ROLL ATTITUDE	ROLL ATTITUDE	ROLL RATE	ROLL ATTITUDE HOLD
DIRECTIONAL	YAW ACCEL	YAW RATE	YAW ACCEL (TURN COORD)	YAW RATE
VERTICAL	VERT ACCEL	NONE	VERT ACCEL	NONE

Table 2. Core AFCS Functions.

AXIS	HEADING HOLD		VELOCITY STABILITY (AIRSPEED < 40 KTS)		HOVER ASSIST		ALTITUDE HOLD (RADAR OR BARO)	
	COMMAND	STABILITY	COMMAND	STABILITY	COMMAND	STABILITY	COMMAND	STABILITY
LONGITUDINAL			PITCH ATT	LONG GROUND SPEED	LONG GROUND SPEED	LONG POSITION HOLD		
LATERAL			ROLL ATT	LAT GROUND SPEED	LAT GROUND SPEED	LAT POSITION HOLD		
DIRECTIONAL	YAW RATE	HEADING HOLD						
VERTICAL							RATE OF CLIMB	ALT HOLD (BARO OR RADAR)

Table 3. ADOCS Selectable Mode Functions.

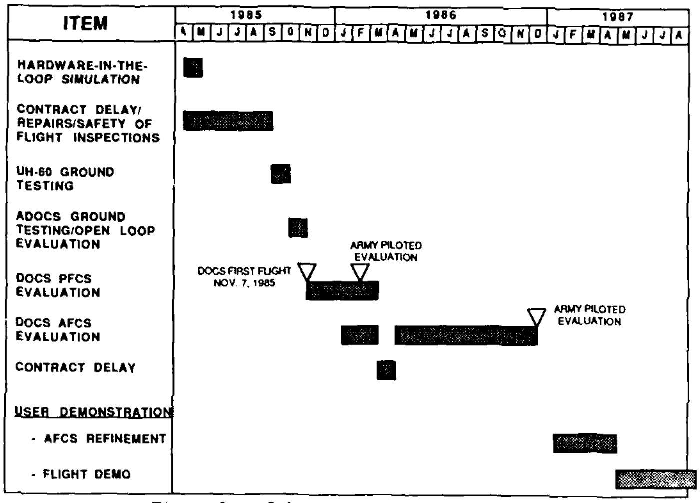

Figure 9. ADOCS Demonstrator Test Activities.

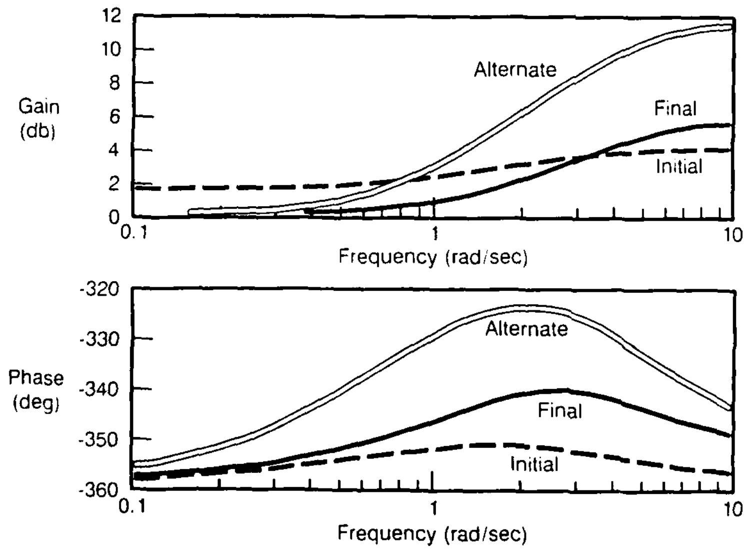

Figure 10. Dynamic Shaping in Longitudinal Axis.

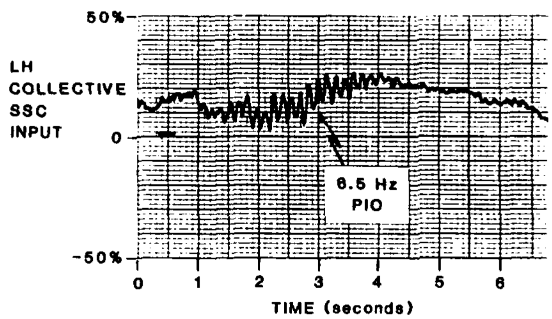

Figure 11. Collective Input Time History.

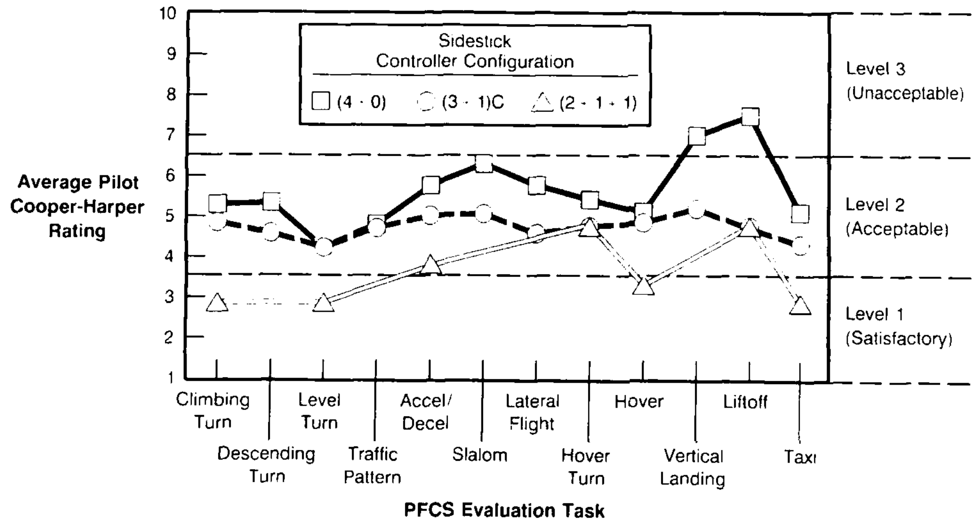

Figure 12. Effect of SSC Configuration on Pilot Handling Quality Rating.

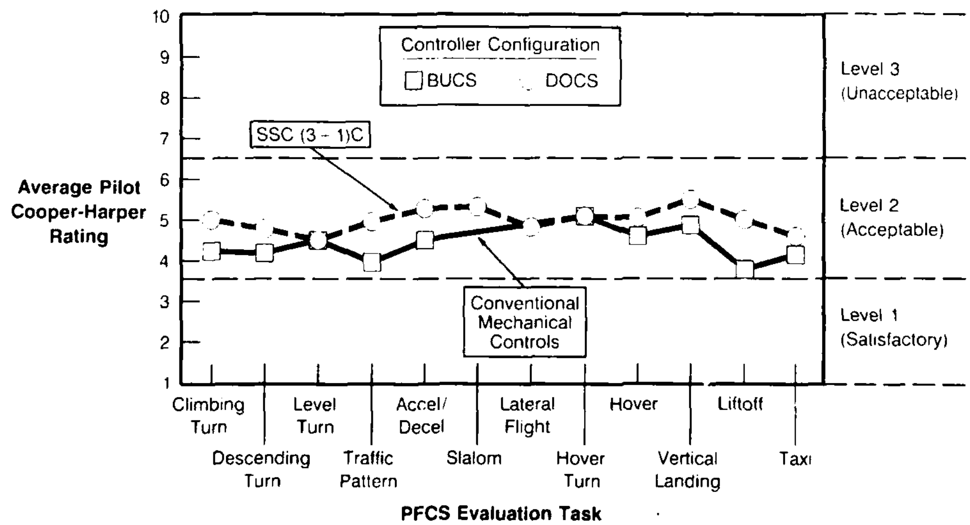

Figure 13. Comparison of BUCS/DOCS Handling Quality Ratings

AXIS	BANDWIDTH (RAD/SEC) W/O COMMAND MODEL	PHASE MARGIN (DEG)
PITCH	2.5	50
ROLL	4.0	50
YAW	3.0	45
VERT	2.5	70

Table 4. ADOCS Stability Characteristics.

AXIS	RESPONSE TYPE	FREQUENCY (RAD/SEC)	DAMPING RATIO
PITCH	ATTITUDE	2.0	1.0
ROLL	ATTITUDE	2.5	1.0
	RATE	5.7	1.0
YAW	RATE	2.0	1.0
VERT	RATE	2.0	1.0

Table 5. ADOCS Command Model Characteristics.

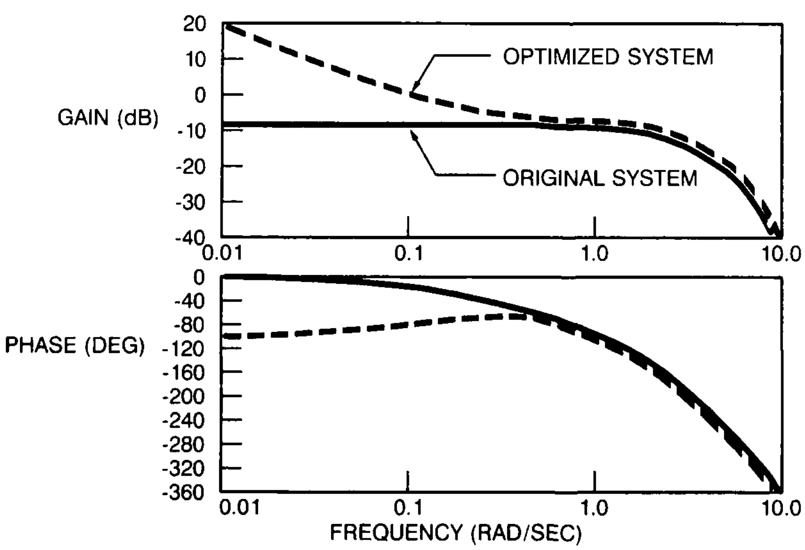

Figure 14. Longitudinal Axis AT/AT Command/Response Characteristics.

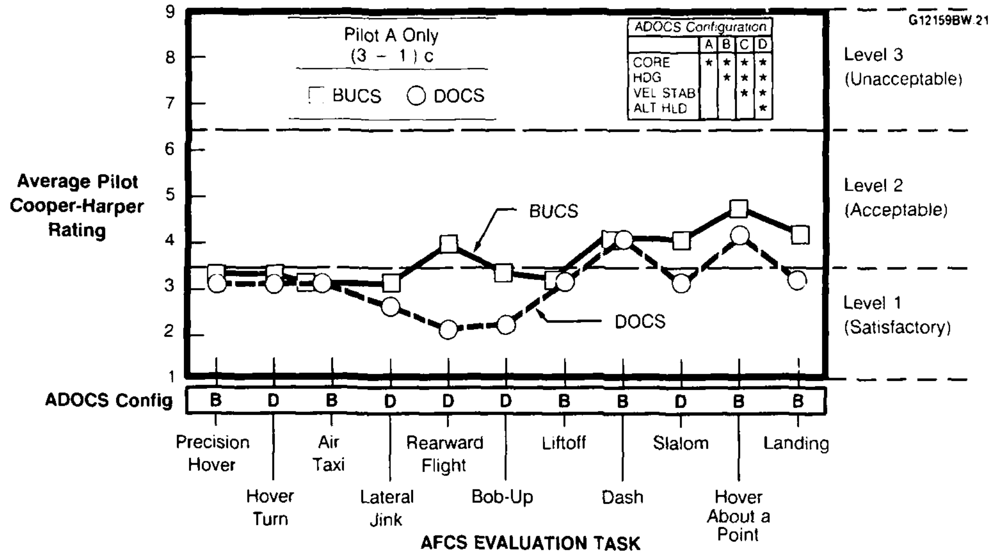

Figure 15. Demonstrator Low Speed Handling Qualities Evaluation

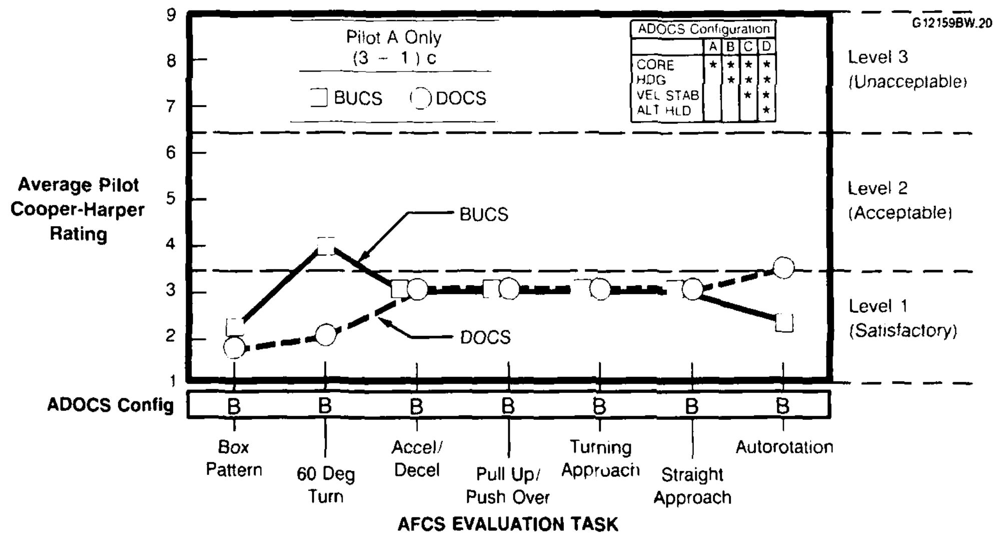

Figure 16. Demonstrator Forward Flight Handling Qualities Evaluation.

MATCHING CREW SYSTEM SPECIFICATIONS TO HUMAN PERFORMANCE CAPABILITIES

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SUMMARY

Despite spectacular advances in display systems and data handling technologies, modern crew systems confront their operators with a staggering volume of codified information which competes for scarce attentional and control resources. Unabated, these increasing psychological and physiological demands have potential to undermine critical technology gains in system performance. While it is generally accepted that the human operator's ability to acquire, process and make effective control decisions using task critical information is a key contributor to system effectiveness, there are significant difficulties in translating this to meaningful action in the processes of crew system design and acquisition. Recognition of this problem has spurred concerted efforts across DoD to attempt to influence early design tradeoffs in favor of an improved match between crew system specifications and operator capability.

Achieving an optimal fit between system capabilities and the perceptual and performance characteristics of the operator requires the presence of at least three elements: (1) Usable Data Resources. Human performance data are needed in a form and level of precision that can be traded off against other design variables; (2) An Effective Interface providing methods and media to support accession and evaluation of these data with respect to equipment requirements. To be effective, this interface must act to lower the cost (time, resources, risk, etc) of acquiring pertinent data proportional to its perceived value. (3) Sophisticated and Motivated Users. Designers, design management and system acquisition personnel need to understand and place value on the use of ergonomics in the design of effective systems. Designing for active presence of these elements requires understanding of and assumes some ability to influence individual, organizational and regulatory variables that jointly support the design and acquisition processes.

I. INTRODUCTION

The evolution of the flight crew system from the early days of aviation to the present has involved a stunning growth of complexity in terms of the demands on the pilot and the sheer number of controls and displays needed to support wide ranging mission requirements (Fig 1). While dramatically extending the capabilities of modern military systems, the technological advances in avionics and information handling technologies over the past few years have also pressed at the limits of operator performance capabilities.

Current attempts to overcome this problem have followed two fundamentally different approaches. First have been approaches typified by the use of multifunction and/or computer driven menu display technology in recent crew systems (Fig 2) which are aimed at reducing the apparent volume of information simultaneously competing for the operator's attention. Aside from any human factors advantages, these approaches provide the major engineering benefit of freeing up scarce crew system real estate thereby permitting the integration of additional avionics technologies that are clamoring for tickets to fly. The major disadvantage of this approach is that critical information may not be immediately available at the moment of need in the rapidly shifting dynamics of modern air combat. Concern over this potential problem has spurred the research and development of new technologies aimed at rapidly reconfiguring the crew system information suite in a manner adaptive to changing circumstances. For example, proposed applications of machine intelligence in the crew system -- as in DARPA's Pilot Associate -- are expected to be able to aid the operator in both the rapid interpretation of information and in the performance of mission tasks -- thereby altering the allocation of man-machine functions in future flight crew systems.

The second major approach is concerned with reducing operator load by matching the bandwidth of crew system controls and displays to the physiological, psychological and psychomotor capabilities and limitations of the operator. This approach stems from ergonomic concerns over the human operator's ability to integrate information from a disparate array of highly codified bits of information into a unified awareness of the situation vital to effective mission performance. A major weakness of this approach is that it depends on driving the state-of-the-art of control/display information portrayal technologies based upon illdefined, little understood and at best controversial models and notions of operator performance. Because of the risks and uncertainties associated with this approach -- i.e. it has tended to be research rather than development -- it has, in the past, lacked the threshold level of support needed to attain critical mass. More recently, research sponsored by Reising (1,2) coupled with spectacular accomplishments on virtual display interfaces by Furness, Kocian and colleagues (3) have provided the fundamental technology breakthroughs needed to rekindle "development" interest in this "human-centered" approach.

The crucial link to the success of either of these approaches, or a hybrid of the two (i.e. a "super cockpit"; fig 3; ref 4) is the ability to translate our fundamental understanding of the human operator into relevant and applicable actions. While a staggering volume of research findings exists, it remains difficult to pinpoint a direct linkage between the implications of this research and the basic insights needed to design these human-centered systems. While human factors researchers typically rationalize or justify the relevance of their projects on the basis of real problems, they generally believe their responsibility to actually solving these problems ends with publication of their findings. Overall, there

appears to be a lack of sensitivity on the part of the behavioral research community to the designer as an end user of this information. In particular, there is little or no understanding of the factors that influence the ability of designers to acquire, process and make effective decisions using ergonomics. As a result, ergonomics information and the knowledge, tools and metrics to use this effectively in system design are urgently in demand. The principal objective of this report is to identify and discuss these factors in the context of the pragmatic options available for the human factoring of crew system design.

II. HUMAN FACTORING ERGONOMICS DATA TO SUPPORT CREW SYSTEM DESIGN

Systematic consideration of ergonomics data in crew system design decisions and tradeoffs appears to be hampered by a variety of interdependent factors stemming from the nature of design problems and process, organizational and regulatory environments, the nature of designers, and the availability and utility of relevant technical knowledge resources (5).

Much has already been documented in the literature on the general logic and formalisms associated with the process of design (6,7). Likewise, many accounts exist of the apparent and hidden complexities associated with the design of military systems (8). In formal descriptions, system design is frequently characterized as an orderly, hierarchical process. However, in reality, it tends to be somewhat chaotic involving many iterative steps, stages and procedures dependent on the control and communications of multiple individuals and organizations with their respective skills, biases and inclinations (9,10).

Fundamentally, the goal of system design is to conceive an artifact whose form and function match a set of defined needs and requirements within defined cost, schedule and material constraints. It is a cumulative function of a multitude of design decisions and tradeoffs which are, in turn, dependent on the information and experience factored into them. Hence, design decisions made without consideration of potentially leveraging information may be suboptimal and may collectively, depending upon their impact on system function, undermine design effectiveness (9,11).

The design decision process (simply schematized in fig 4) is best represented as a subjective integration of information resources and personal experience which is, in turn, constrained by limitations of available time and resources. The nature of this integration is not well understood though it probably involves a variety of cognitive processes including analytic and analogic reasoning, pattern recognition, informal hypothesizing, and mental modeling which are often collectively referred to as creative intuition. At different times, single individuals or individuals working together as a team may be involved. It is an iterative process, recurring at all stages and levels (i.e. system through component levels) of a given design.

The interdependence among the myriad factors which contribute to the design of complex systems makes it difficult to predict the influence of any single factor, bit of information or decision on a given design. In contrast to this apparent unpredictability, the pressures of limited time and resources typical in system design drive designers to bias decisions and tradeoffs toward reduction of uncertainty and risk. Hence, the selection of appropriate baselines -- a proven system or subsystem analogous to the one under development -- will generally account for the largest portion of variance in a given design's effectiveness. In other words, choosing good baselines should reduce the risk to a given system's effectiveness. In military systems the temptation to consider new technologies -- well beyond the initial design phases -- introduces a sizable risk to design effectiveness. All in all, it is not surprising that few complex system designs are original or new. Rather, they typically are variants or adaptations of existing designs.

Effective design, therefore, involves a skillful blending of past baselines with new decisions and tradeoffs, counterbalanced to minimize risks to achieving pre-defined functionality within material, cost and schedule constraints. Raising the efficiency with which information is considered and factored into design decision-making should, by inference, raise the probability of design effectiveness.

Ironically, enhancing design effectiveness by improving design access and utilization of design-relevant information may be hampered by the fact that designers are already deluged by too much information competing for their time and attention. In a series of studies, Allen (12) has convincingly shown that well over ninety percent (90%) of the information factored into technical decisions by engineers already resides, at the time it is sought, in personal files or in the files of trusted colleagues (Fig 5). This observation is particularly interesting in view of the information explosion in a range of technical areas of potential value to system design. The extremely limited channel capacity for consideration of new information suggested by these data indicates that the opportunity for human factors information to impact system design decisions is, at best, highly constrained. More specifically, this finding suggests that an optimal strategy for improving the impact of human factors information on system design must focus on raising the perceived value while lowering the perceived costs of this information for the system designer. Indeed, simply understanding the key variables that drive the variance between perceived and actual values and "costs" associated with technical information by system designers should be a principal area of concern for human factors researchers and practitioners.

III USABILITY OF ERGONOMICS

Achieving an optimal fit between system capabilities and the perceptual and performance capabilities of the operator is dependent on a complex set of factors dictated by the nature of design, the inclinations and biases of designers, and the availability of usable data resources. In particular, human performance data are needed in a form and level of precision that can be traded off against other design variables.

While a good deal of potentially useful human performance data exists, these data have had very little direct impact on the design of crew system interfaces. In large measure, the failure to translate relevant research findings to applications seems to lie with the "perceived" value of these data in terms of the costs and risks in their <u>accession</u>, <u>interpretation</u> and efficient <u>application</u> to system design problems.

A. ACCESSIBILITY. This refers to the ease and precision by which information may be acquired. Needless to say, accessibility is a significant contributor to the perceived "cost" of information by designers (12). Hence, while it is important that ergonomics information useful to a given crew system specification problem may exist, it is likely to be embedded in a staggering volume of extraneous information distributed among countless journals, periodicals, government and industrial technical reports, etc. Furthermore, the contextual and theoretical frameworks within which researchers typically generate, disseminate, and otherwise organize technical information are not necessarily common with the logical framework or needs of the practitioner. For practical purposes, designers may not readily find needed information where it is expected to be located (11).

B. INTERPRETABILITY. This generally refers to the ease with which information content can be deciphered and understood. This too is a critical problem with traditional sources of human factors information and knowledge. Researchers typically feel little responsibility to the "applications world" beyond reporting their findings into the scientific literature. Hence, interpreting scientific communications will likely add considerable overhead and in fact may be a barrier for the practitioner in terms of his or her ability to evaluate the relevance of human factors information to the problem at hand (11,13). The human factors profession is particularly guilty of not "human factoring" the presentation of human factors data for practitioners (14).

C. APPLICABILITY. A major contributing problem to the usability of human factors are the obvious difficulties and continuing controversy regarding the relevance and translatability of research data to practical applications (15,16). Independent of the highly controlled circumstances under which data are collected, the experimental conditions posed by researchers are often so synthetic that it requires a major stretch of the imagination to find analogous circumstances in the real world to which these conditions might relate. The concern is that data collected under such highly limiting conditions cannot be reasonably extrapolated to multivariate conditions where many contributions to variance from interaction effects remain unaccounted for. Unfortunately, this criticism is also true of most applied multivariate studies in which the problems of comparision and extrapolation between experimental and dynamic "real world" contributors to variance are severely compounded. Therefore, if one gauges the applicability of ergonomics based solely on the assumption that it is to be used by designers seeking "cookbook" answers, then ergonomics as a viable discipline is doomed to failure. Neither the time nor resources are ever likely to exist, particularly in the midst of design problem solving, to parametrically evaluate (with any certainty) the conditions active in an interactive real world system problem (17). The usefulness of these data seems to lie not so much with their direct translatability to multifactor conditions (though some "cookbook" answers exist for some "cookbook" questions), but rather with their use as an aid or means to answering questions by providing cues, clues and confirmations supportive of the designer's reasoning processes.

Designers commonly decompose design problems (e.g. systems to subsystems as in Fig. 6; Ref 18) into logical subsets of design questions and tradeoffs while attempting to hold associated risks constant through baselining (Fig 7). Depending on factors such as the availability of "cookbook" answers, high value issues for which uncertainty remains may be further decomposed into higher resolution questions for which the "best" answers within time and resource constraints will be sought. The process of generating higher resolution questions and matching to the best resolution answers probably involves informal theorizing, pattern recognition, analogical reasoning and other processes all of which may be subsumed as design "intuition" and creativity (19). Hence, for example, designers of controls and displays frequently ask questions of human factors practitioners in which the variables of interest are highly constrained (20). While, in many instances, this may facilitate a "direct" match to the empirically based research literature, more often than not, matches to the extant data are made on the basis of inferences, the seeking of cues or clues, or in the confirmation of informal predictions.

It is interesting to note that while this process is not well understood, it is also somewhat analogous to that followed by researchers in the piloting phase of research when they are seeking the "sweet spot" among the variables of interest to study. Though this phase of research is rarely treated explicitly in the empirical literature, it clearly involves skills critical to good research -- independent of our current state of understanding of the processes which govern it. Similarly, examples of 'good' human engineering abound in which the supporting rationale for key decisions or tradeoffs is nothing more than an artifact of retrospective reasoning. Perhaps, therefore, the major differentiating element between "good" researchers and "good" designers is that researchers are compelled to formalize their observations of causes and effects in a procedural context while designers find satisfaction in the informal confirmation of their inferences and predictions in the "trial and error"-like synthesis of a design.

The "bottom line" to this discussion is that while much apparently relevant ergonomics information exists, its application to system design problems is not at all straightforward. It is difficult to use as a basis for prediction and its use carries many risks for the designer. Coupling this difficulty with the risks associated with its accession and interpretation severely reduces its perceived value to the system designer. The successful matching of crew system specifications to human performance capabilities is ultimately dependent on (1) raising the absolute value and lowering the costs of ergonomics in system design while (2) manipulating the perceived value and costs of this knowledge within the crew system design community. The first issue is dependent on a reassessment of responsibilities and roles within the profession. By this, I mean an assumption by the profession of greater responsibility in closing the gap between responsive research and application needs while effecting a shift in focus toward developing the models, methods and metrics needed to transition the state-of-the-art of human engineering knowledge

and practice to the system design process. The fact that this is beginning to happen in conjunction with concerted attempts at consolidating and institutionalizing the ergonomics knowledge base[1,2] leads me to believe that the perceived values and costs of ergonomics in system design should naturally begin to shift in response. Facilitating this shift in the US are major changes in DOD system acquisition policies which are placing new emphasis on requirements for human factors specification (e.g. MANPRINT in the US Army; Manpower, Personnel and Training System Project Office in the US Air Force). Emerging information access and decision support system technologies integrated into computer aided design and engineering systems (CAD CAM) such as the AF Cockpit Automation Technology Program, the AF Designer's Associate and the Army/NASA C^3I Program will eventually aid future designers to efficiently access and tradeoff human performance data with other technical information germane to the effective design of crew systems.

IV. CONCLUSIONS

Matching system specifications to human performance capabilities and limitations has acquired greater legitimacy as a design goal for future crew system interfaces. Meeting this goal with respect to human sensory, perceptual, cognitive and psychomotor capabilities cannot presently be achieved in a systematic fashion employing traditional engineering practice. The problem results from the costly accessibility and uncertain applicability of ergonomics data coupled with the conservative inclinations of system designers and the cost/schedule pressures of the acquisition process. In the past, the perceived gain of using ergonomics has been too low given the costs (time, money and risks) of accessing and practically applying this information in the system design process. The emergent availability of application-oriented data sources, access and decision support system technologies and shifts toward regulatory demand for ergonomics in the DoD system acquisition process will collectively raise the value for designers of factoring ergonomics into system design.

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1 There is a critical need to distill and consolidate useful human factors knowledge so that it may be available as a resource to [illegible] system designers. A significant effort in this vein is the Integrated Perceptual Information for Designers (IPID) Project which is a US/NATO AGARD multiagency supported effort to develop human performance data resources for system designers. IPID has supervised the review and evaluation of many thousands of research studies. The small percentage rated as reliable and applicable has been consolidated and packaged into a variety of communications media. The first is a two volume reference Handbook of Perception and Human Performance (21,22) for human factors specialists. Second is a four-volume Engineering Data Compendium (23) in which the presentation of these data has been human-factored to enable their direct use by system designers. IPID is also sponsoring and developing educational opportunities to train and sensitize system designers in the value and application of human performance data to crew system design.

2 The Crew System Ergonomics Information Analysis Center (CSERIAC). Under the auspices of the DOD and in conjunction with the Tri-services and NASA, the AAMRL will establish and host in mid-1988 an institute with responsibility for the maintainance, update and analysis of ergonomic knowledge resources needed to support crew system design (24). CSERIAC will provide a full range of technical information services in support of crew system research, design and development serving the government, and industrial and academic sectors in the US and abroad. The key function of CSERIAC will be to build a network among relevant experts and other knowledge sources while developing the resources and media to draw upon and focus this expertise to solve problems, achieve expert concensus, and aid planning for more effective use of ergonomics data in the system design process.

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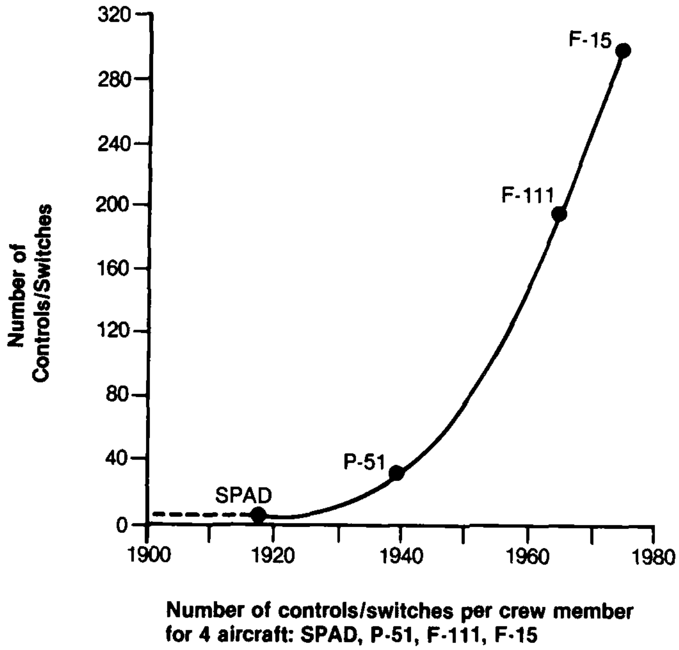
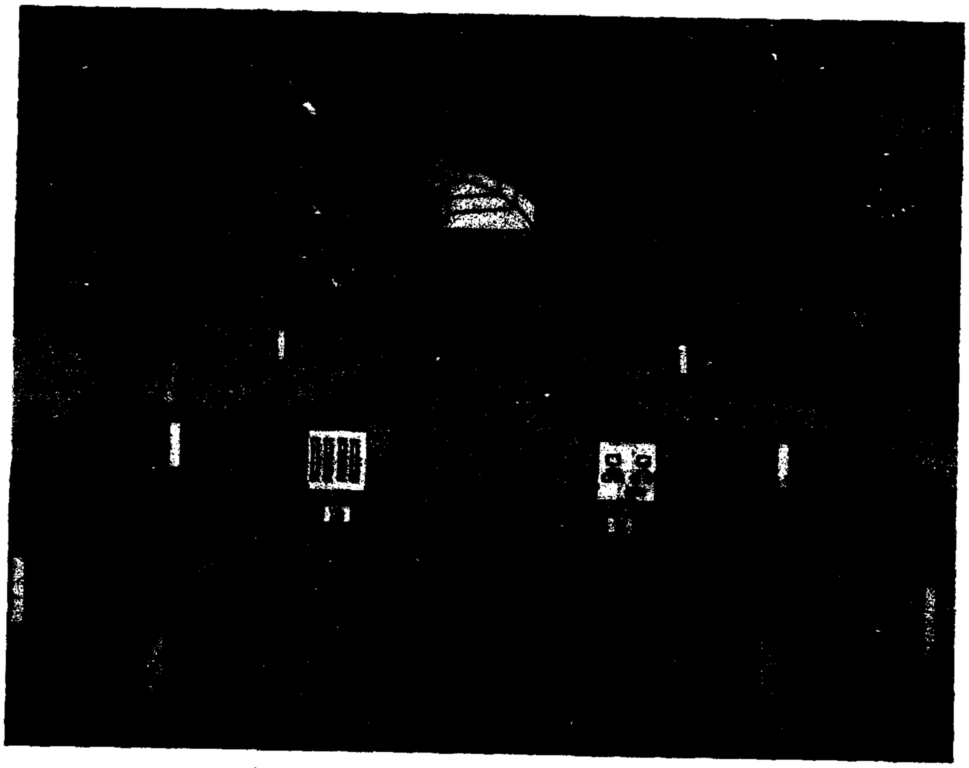
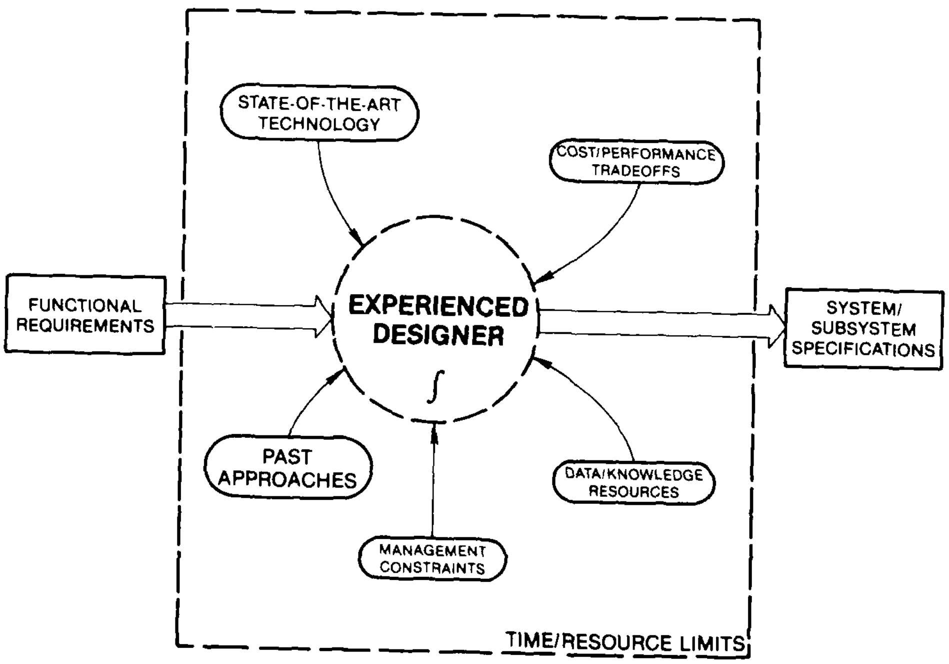


1. Exponential growth in controls and switches per crew member shown from 1918 to 1976 for four combat aircraft.

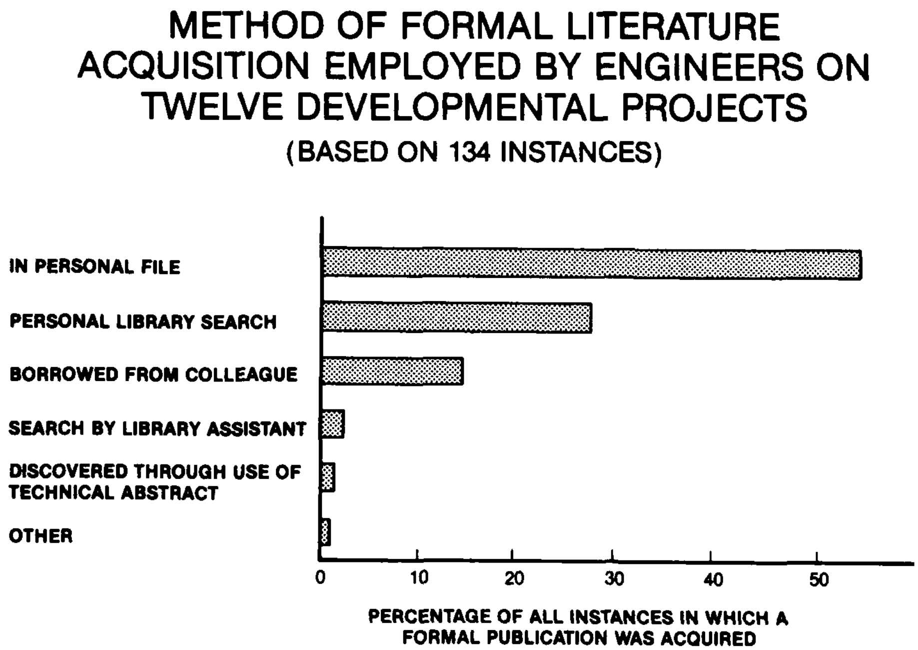
2. F-18 "glass cockpit".



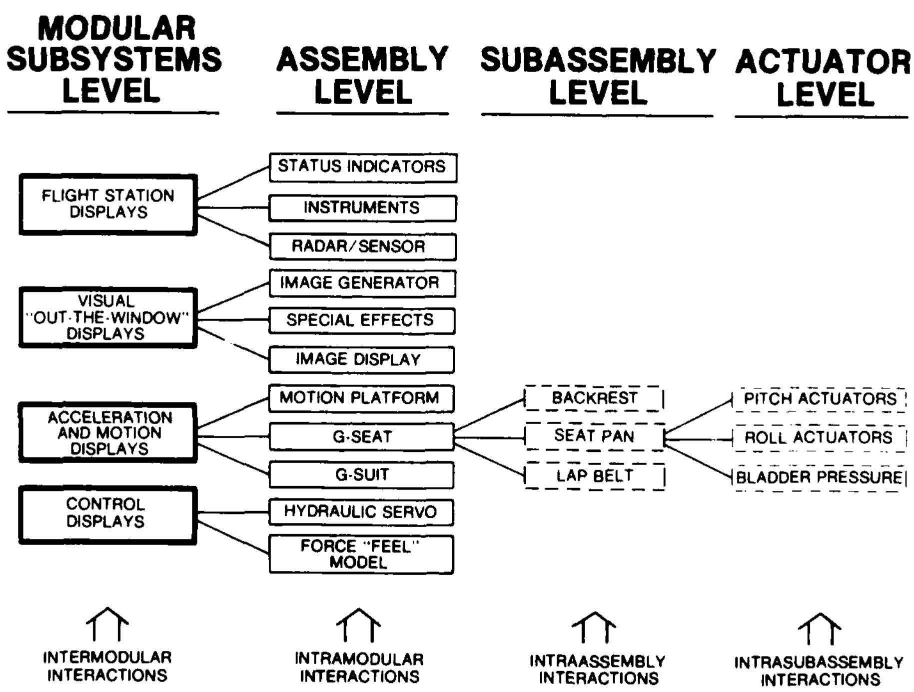
3. Artist rendition of AAMRL virtual crew system.



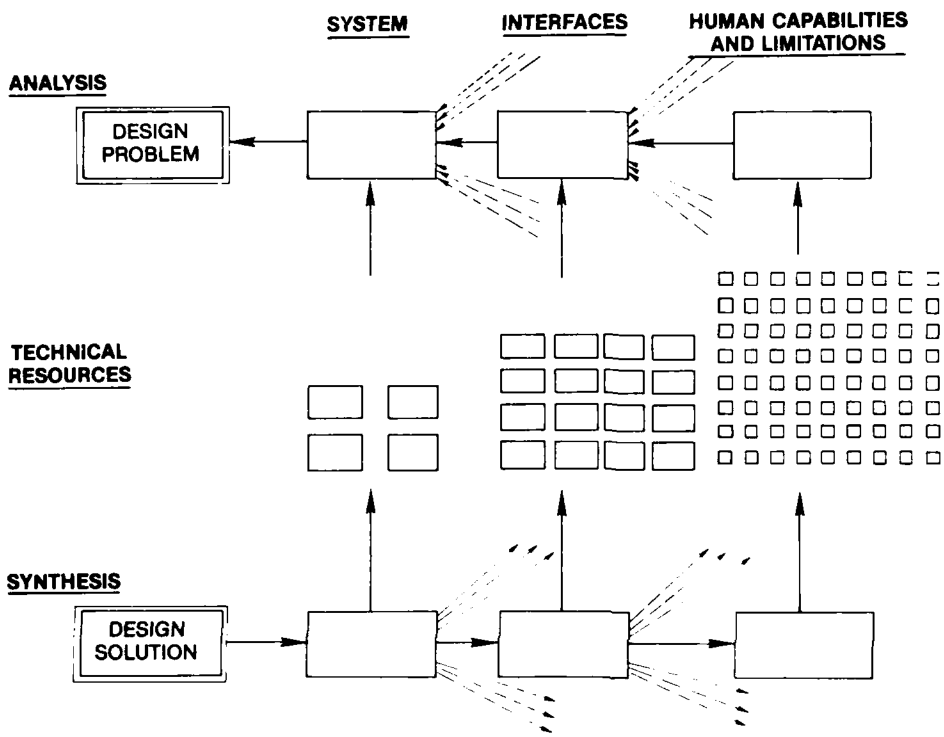
4. Process schematic of design decision making.



5. Information acquisition by engineers. Adapted from Allen, 1976.



6. System/subsystem decomposition for an aircraft flight simulator.



7. Schematic showing different levels to which a design problem may be decomposed. As system issues are decomposed to finer subsets, there is a corresponding proliferation of subsystem issues (as shown in fig. 6) with questions and tradeoffs to resolve. The level to which a given design problem is reduced is dependent upon the availability of usable baselines, technical information resources and the degree of risk to system effectiveness associated with resolving a given issue. The process of resolving questions or issues at a given level of resolution using the "best answers" offered by available technical resources is not well understood. Neither do we understand the collective re-integration or synthesis of these responses within and across individuals which contributes to resolving the broader levels of issues and tradeoffs in a given design.

INTEGRATED CONTROL AND AVIONICS FOR AIR SUPERIORITY

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ABSTRACT - The Integrated Control and Avionics for Air Superiority (ICAAS) Program is a United States Air Force Advanced Development Program to design, develop, and demonstrate selected fighter aircraft technologies needed to kill and survive when outnumbered in air combat engagements. Design emphasis is placed upon functional integration of sensors, fire control, flight control, weapons and interface with the pilot to achieve improved beyond-visual-range (BVR) multiple target attack capability with effective transition to close-in combat (CIC). Data from multiple onboard sensors is blended for improved target detection, track, and identification functions. Fire control algorithms compute multiple target prioritizations and missile launch solutions using active or passive sensor modes. Flight control algorithms include attack and defensive guidance functions which aid the pilot in maximizing launch opportunities while minimizing threat exposure. Evasive maneuvers with countermeasures are used to survive attack by threat homing missiles. Improved cockpit presentation of engagement data enhances pilot situation awareness to allow informed engagement decisions. Data link internetting between friendly aircraft reduces dependency on verbal communication and greatly enhances intraflight coordinated attack. Piloted simulations and flight testing will be used to develop and validate ICAAS technology in a realistic multitarget environment. This paper presents details of the ICAAS concept and design approach.

INTRODUCTION - Recent literature is filled with descriptions of an increasingly complex air combat environment which will challenge the ability of USAF tactical fighter aircraft forces to establish and maintain air superiority. Experts generally agree that enemy forces will have a significant numerical advantage. According to Col Jeffrey G. Cliver, Chief of the Tactical Division at the Directorate of Operations, Hq USAF, "In the next war we could be outnumbered by six or more to one in any given air battle" (1). Current USAF operational fighter aircraft are very effective in attacking single targets, but sensor, weapon and subsystem design limitations inhibit performance capability against multiple targets, especially at beyond-visual-range (BVR). Onboard sensors seldom provide sufficient information to detect all potential threats or to identify non-cooperative targets. The pilot must visually confirm identification, thus forcing him into short range dogfight situations where a numerically superior force usually has the advantage. Semi-active missiles, such as the AIM-7, require continuous radar coverage in radar single target track mode all the way from launch to target arrival. This allows only the highest priority target to be attacked at any given time. If a pilot is surprised by a higher priority threat during a missile fly out, he must abandon radar illumination of the original target resulting in the missile going ballistic. Dedicated control and display formats for each subsystem force the pilot to mentally integrate data at hand to assess the situation and make engagement decisions. Communication with friendly aircraft using radio conversation is time consuming to the pilot and very prone to errors as messages become garbled with multiple aircraft. For all these reasons, attacking pilots attempt to isolate and engage single targets one at a time. The primary commandment of air-to-air warfare is: "If at all possible, engage only if you have the advantage. This means that a flight of two always attempts to engage a single bogey" (1). This tactic can be used very effectively to counter an enemy force of limited numbers, but when the enemy has a significant numerical advantage, major improvements in onboard system capabilities are needed. Multiple targets and threats must be addressed simultaneously, with different actions appropriate to each, rather than a series of actions against a single target. As stated by Col Hoffman (2), "Clearly the challenge for our future fighters remains with our ability to build in the technology to counter a numerically superior enemy".

New technology developments are taking place which will provide tactical fighter pilots with much needed system enhancements. Advanced sensors will provide greater accuracy in surveillance and target recognition (3). For example, infrared sensors can augment radar by providing target position data without emitting signals which can be detected by electronic countermeasures. The Advanced Medium-Range Air-to-Air Missile (AMRAAM) will allow a fighter to engage several enemy aircraft at the same time, since constant target illumination is not required (4). Advanced countermeasures will provide additional information about the enemy and reduce the effectiveness of his onboard systems. Digital data internetting will provide an intraflight exchange of situation data and target assignments without depending on voice communications. Increases in onboard computer power will enhance data processing capacity. These are only a few of many ongoing developments, but enough to make an important point. Future fighter aircraft will be capable of generating an enormous amount of data from a multitude of subsystems. However, more must be done to help a pilot manage these subsystems, derive critical situation information and sort out the best engagement options to consistently engage and defeat a larger enemy force. This cannot be accomplished with a collection of independent or self contained subsystems. Integrated configurations must be developed with capabilities to provide the pilot with a summary assessment of the combat situation, recommended engagement options, and automatic execution of tasks requested by the pilot.

The ICAAS program was originated to address these design challenges. The program is sponsored by the Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio. Development activity will be divided into three major categories; attack management, flight management, and pilot/vehicle interface. The Flight Dynamics Laboratory will be responsible for overall program management, with attack management development and integration support from the Avionics Laboratory. Flight testing will be performed at the Air Force Flight Test Center, Edwards AFB, California. Contracts for system development were not yet announced at the time of this publication. This paper discusses content of the three ICAAS development areas followed by the program approach to system integration and test and evaluation.

Attack Management - Algorithms are being developed which form an interface between the pilot and the onboard sensors and weapons. The purpose is to provide the pilot with information to maintain a high level of situation awareness. These algorithms will perform functions of a) sensor control, b) data fusion, c) weapon control and d) internetting (intraflight data exchange).

a. Sensor Control - Pilot workload associated with the task of sensor control can be extremely high. A modern radar can have more than twenty different operating modes and a pilot can easily dedicate most of his attention to operating the radar. Most pilots will become familiar with some of the modes and ignore the rest. Since future fighters will likely have multiple sensors, it is easy to see how the pilot of a single seat aircraft could easily become overwhelmed with manually operated sensors. ICAAS automated sensor control will support particular attack modes desired by the pilot, including active mode with sensor energy emissions allowed (such as radar), low probability of intercept mode with limited energy emissions allowed, and covert mode with use of only non-emitting sensors (such as infrared). Individual sensor functions such as on/off switching and sensor pointing are included, with provisions for pilot manual control whenever necessary. Coordinated use of multiple sensors allows maximum total scan volume coverage (see figure 1) or other control strategies depending on needs driven by the battle scenario.

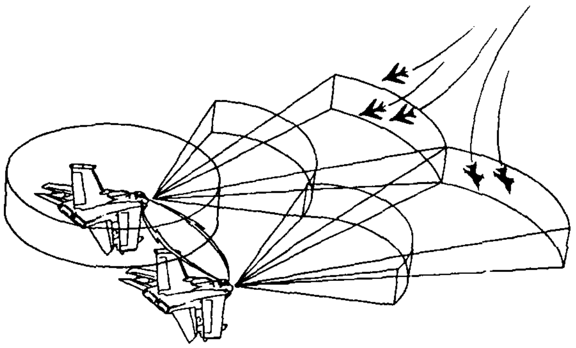

FIGURE 1

b. Data Fusion - Any individual sensor may not be able to assemble all desired data concerning a particular target, especially for confirming positive identification of BVR non-cooperative targets. ICAAS data fusion algorithms combine track file data from multiple sensors to derive a total summary of known target characteristics, resulting in a much higher probability of identification. Another valuable output of data fusion is a target kill assessment. It is important for a pilot to establish whether a BVR missile launch killed the intended target. If so, he may turn his attention to other potential threats. But, if the target was not destroyed, he may become vulnerable to attack from the original target by redirecting his attention. Data fusion from multiple sensors improves confidence in the kill prediction; if both an infrared flash is detected at expected missile impact time and radar velocity goes to zero, a kill is highly probable.

c. Weapon Control - Baseline weapons for ICAAS fire control system functions are AMRAAM, AIM-9, and 20mm gun. Data from target track files are used to compute ownship missile launch envelopes and threat envelopes against the ownship. In addition, recommended target priorities will be established considering such factors as weapon status (quantity & type), relative geometry to the enemy aircraft, guidance requirements of in-flight missiles, and pilot designation of priority target. Fire control algorithms enable simultaneous launch against several targets, with appropriate post-launch guidance provided to the missiles. An all-aspect director type gunsight is available to take advantage of gun opportunities if the engagement collapses to close-in combat. Finally, the pilot can use information provided to make decisions on how to attack and how much automation to allow from the onboard weapons control.

d. Internetting - Intraflight digital data link capability will be implemented to permit exchange of sensor data (track files), targeting assignments and tactics. This allows extension of data fusion algorithms to include known target data from all cooperative sensor sources. A sample benefit of this approach is the case of a covert attack using an infrared (IR) sensor. A single IR sensor can precisely measure

line-of-sight to a target, but cannot directly determine target range. To get an accurate range measurement, a burst of radar energy may be required and the target may be alerted. Two internetted fighters can triangulate using line of sight measurements to accurately determine target range while remaining covert. In addition, all internetted fighters get a consolidated summary of situation data and indication of targeting assignments. Fighter effectiveness will increase dramatically compared to coordination using voice communications. The ICAAS program is not developing data link technology, only developing functions which depend on its presence.

Flight Management - ICAAS flight management involves guidance and control of a fighter aircraft during the engagement mission phase to achieve combat positional advantage. The previously discussed attack management algorithms will only provide the pilot a high level of situation awareness. When a flight is opposed by superior numbers of enemy aircraft, the best engagement option of several alternatives may not be obvious, and more than just good situation awareness is required. Flight management algorithms consider factors relevant to planning and executing flight trajectories which position the aircraft for maximum probability of target kill and maximum probability of ownship survival. Flight trajectory information must be displayed to the pilot for manual control, or coupled to the flight control system for automatic flight. The level of automation needed to achieve the most effective combat performance is a critical issue to be examined throughout the ICAAS program. In any case, the pilot must be able to alter the recommended solution.

Due to the extremely dynamic nature of air combat, computation of flight trajectories within appropriate time constraints is a significant design challenge. The design must minimize decision errors due to incomplete, imprecise, or false sensor information. Control solutions must remain unpredictable to the enemy yet reactive to enemy actions. Defensive flight maneuvers enhance survival against threat homing missiles by properly timed evasive maneuvers in conjunction with use of expendable or electronic countermeasures. Offensive and defensive trajectory computations must be properly balanced so that attack can be executed with defensive contingencies in mind, and defensive maneuvers can be implemented without abandoning an offensive posture.

Flight management algorithms must interact with attack management. In many cases flight management information affects attack management target prioritization solutions. For example, when assigning attack priorities for enemy aircraft, higher priority should be assigned to aircraft which are in a position to defeat defensive maneuvers. Flight management must also consider wingmen status and shared data sources which are available from the internetting function of attack management. Mutual support from cooperating fighters will enhance overall effectiveness. Specific functions of ICAAS flight management include:

a) Navigation - A precision navigation capability is being developed for computing ownship inertial position and state information (attitude, velocity, acceleration, etc) throughout the time of flight. A common source of state data is used for navigation computations, flight control inputs, stabilization/correlation of multiple target sensors, and fire control calculations of missile launch envelopes. This supports efficient functional integration while reducing the required number of onboard motion sensors.

b) Attack Trajectory - Algorithms provide the pilot with multiple-target attack trajectory control references and recommended control solutions which can be coupled to the flight control system. Automatic control modes shall be activated only by positive pilot action. BVR attack trajectories are based upon avoiding threat launch zones while solving ownship missile launch constraints. Transition to CIC includes a precision weapon pointing control system for short range missiles and aerial gunnery.

c) Airframe Performance - Flight management aids the pilot in maintaining aircraft performance which is appropriate for the combat situation. Energy Maneuverability (EM) information permits full exploitation of aircraft maneuver potential to achieve combat positional advantages. EM will relate current state conditions to available maneuver potential and compute the best combination of altitude, airspeed, power setting, etc. to minimize a mission critical component of airframe performance. For example, a pilot may desire to fly to an energy state which provides maximum launch range for a medium range missile, then quickly transition to conditions for optimal endgame evasive maneuvering. McAtee (5) has emphasized the importance of an aircraft's ability to rapidly transition from one flight condition to another, rather than attempting to maintain greatest energy state. In other situations, the pilot may want to present minimum radar cross section or infrared signature to a particular enemy aircraft. He may want to fly a minimum time or minimum fuel intercept trajectory. These are examples of conditions which are being investigated during ICAAS flight management development. Modes which are implemented will be prioritized by the expected payoff in combat performance. In any case, the flight management implementation will assist the pilot in sorting feasible from infeasible engagement options and optimizing aircraft performance appropriately.

d) Missile Avoidance/Evasion - Studies have shown that precisely timed and controlled endgame evasive maneuvers can defeat attack by a threat homing missile (6). ICAAS flight management computes avoidance and evasion flight trajectories for pilot manual or automatic control. Avoidance maneuvers are defined as actions prior to threat missile launch, or early in the missile time of flight, which are intended to fly the aircraft to a safe location beyond the missile flight envelope. Mid-course or endgame maneuvers are performed to create a safe miss distance when avoidance is not possible (see figure 2). Information from ownship and internetted sensors is used to gather information about the

inbound missile and to compute appropriate defensive maneuvers. Coordinated use of available countermeasures provides greater miss distance than possible with maneuvering alone. Significant increases in probability of survival are expected compared to manually flown "rule of thumb" defensive maneuvers which pilots are forced to use at present.

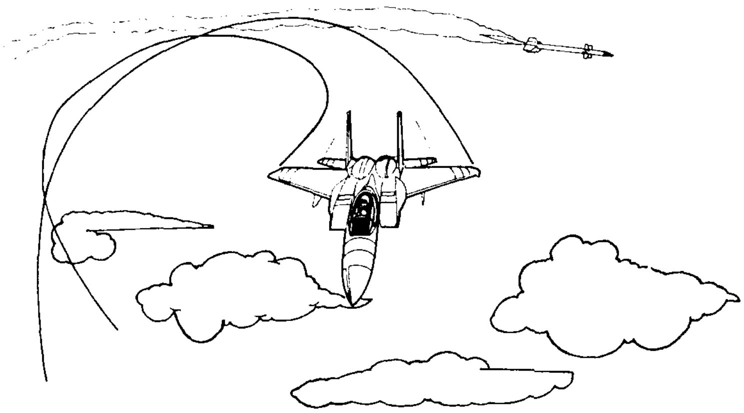

FIGURE 2

e) Resource Management - Available onboard resources are considered when computing ICAAS flight trajectories. Resources are defined as weapons, fuel, and countermeasures. For example: a) the pilot will be informed if a minimum time intercept trajectory would exhaust his available fuel supply, b) if all medium range missiles have been expended, BVR attack trajectories would be discarded in favor of CIC weapons or egress from the engagement, c) missile evasion algorithms should not consider an option for dispensing a flare against an infrared missile if all flares have been expended.

Pilot/Vehicle Interface - Pilots make decisions based on perceived information, so by obtaining more complete information and presenting it more concisely, situation awareness can be improved, and the best engagement decisions made. Techniques are being developed to display both ownship and supporting aircraft status. Pilots may then make appropriate decisions in coordination with friendly aircraft. For instance, display of targets designated by other friendly aircraft reduces the probability of two pilots attacking the same target (unless help is requested).

Significant cockpit design issues must be addressed to enable a pilot to maintain situation awareness with reasonable workload in complex aerial engagements. Efficient data management techniques must be utilized to provide timely and relevant information in a format easily understood by the pilot. The pilot/vehicle interface (PVI) must be integrated with the rest of the aircraft to achieve the necessary data transfer efficiency and resulting pilot effectiveness. The ICAAS program is examining cockpit control/display features and automation versus manual task allocation to define an advanced air-to-air cockpit design. Color multifunction displays will be used to present tactical situation data, weapon delivery information, threat warnings, and recommended flight trajectories. A helmet mounted sight/display is being used for sensor cueing and threat warning. Interactive voice control is used as an alternate to manual control for functions such as primary mode selection, display control, and data requests. All of these crew system technologies are planned for ICAAS flight demonstration.

A major ICAAS goal is to provide functional harmony between the pilot and the advanced attack and flight management algorithms. The amount of automation that a pilot needs, such as recommended engagement decisions and automatic control coupling is an important issue. According to Moss (8), this depends upon the kind of task and level of pilot performance. A task such as BVR target identification must be automated because the pilot cannot contribute to the process. Automated defensive maneuvers in response to a threat homing missile may be automated, with pilot consent, due to the precision control and timing requirements. Offensive attack steering is a task where the pilot might best apply his inherent flying skills. A proper balance of manual and automatic task allocation will be required to achieve the desired combat performance.

System Integration - The ICAAS program is emphasizing system integration as a technology, not just an implementation detail, thereby leading to higher system performance levels through synergistic combination of information. Integration is an interactive process which begins with concept definition and is continued through final testing. Complex interactions between attack and flight management functions and interfaces with sensors and weapons must be identified This process is not complete until both known and unanticipated problems are solved. To accomplish this, a well structured test environment is required to control the number of variables at each integration step for isolation of

error sources. Rapid prototyping is being used as soon as possible, before actual hardware and software exist, to validate the overall ICAAS concept, as depicted in figure 3. Software modules will be introduced as they are developed with early emphasis on executive and built-in-test functions. Hardware emulation will be used until actual hardware is available, with off-the-shelf processors used to minimize risk to the program.

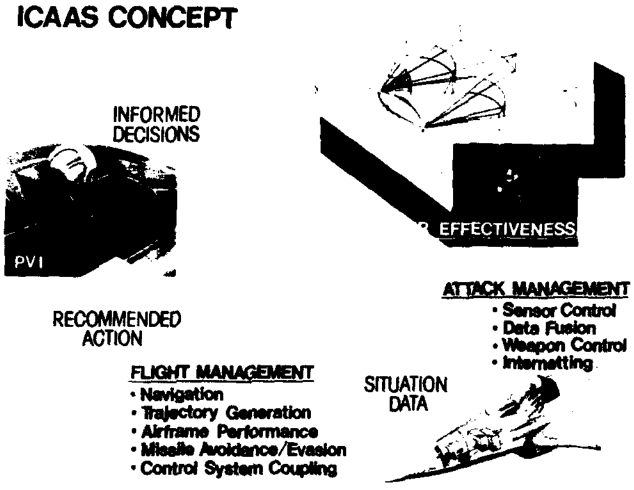

FIGURE 3

Software development and integration is a major task within the ICAAS Program. The Department of Defense standard Ada software language is being used for all software development. Use of Ada is expected to reduce software development cost, provide better insight to the integration process, and maximize technology transition opportunities. Past and ongoing flight demonstrations of flight critical software in the Ada language have provided sufficient confidence that Ada is suitable for the ICAAS Program (9).

Hot bench and hardware-in-the-loop simulation testing is being used to integrate software and hardware components. The total system must perform according to design specifications and must operate in real time. Pilots evaluate the ICAAS system as it matures, to assure information is presented in a manner resulting in effective decision making with acceptable workload.

Test and Evaluation - The primary objective of ICAAS test and evaluation is to demonstrate feasibility and performance capabilities of the ICAAS technologies. The overall performance goal is a ten to one kill ratio when outnumbered by four times as many enemy aircraft. Capabilities of enemy forces are based on 1995 projections. Pilot in the loop simulation and flight test experiments are used to evaluate ICAAS performance in realistic air combat environments (see figure 4).

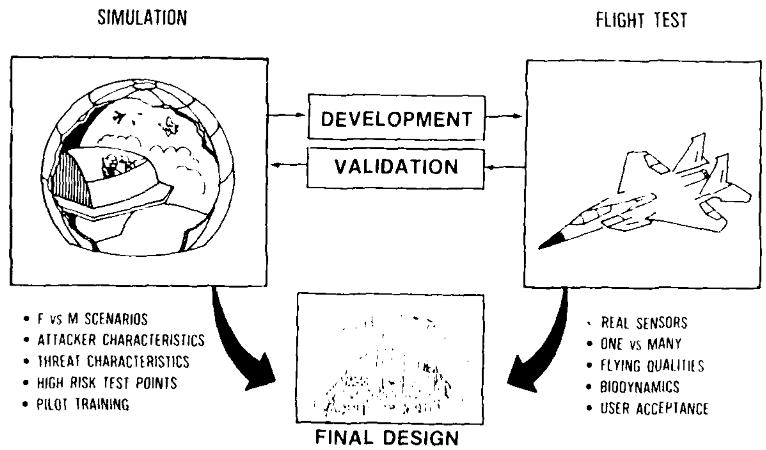

FIGURE 4

Formal, high fidelity, interactive piloted simulation will be conducted to measure the combat performance of four internetted ICAAS aircraft engaging up to sixteen enemy (red) aircraft. An orderly buildup in complexity is expected, starting with two blue versus two red. Blue aircraft utilize two cockpit domes which include crew stations fully configured with ICAAS controls, displays, and information processing. Out of cockpit visual scenes include threat and friendly aircraft, appropriate sky/earth references, and missiles. Manned stations are used to represent the remaining two blue aircraft. Red forces consist of an equal number of manned stations and digital aircraft models. Test conditions include a variety of realistic mission scenarios.

An advanced baseline sensor suite is being modelled during the ICAAS simulations. The baseline suite consists of a multi-mode radar with an Electronically Steerable Antenna (ESA), Infrared Search and Track System (IRSTS), Laser Tracker/Ranger (LTR), Radar Warning Receiver Fire Control Interface Software (RFIS), Airborne Self Protection Jammer (ASPJ), Missile Warning System (MWS), Joint Tactical Information Distribution System (JTIDS), Identification Friend or Foe (IFF), Global Positioning System (GPS), and Inertial Navigation Assembly (INA). Tradeoff studies refine this baseline into a final sensor configuration which results in the most effective combat performance. Realistic sensor configurations and capability limitations force attack and flight management algorithms to cope with less than perfect situation information.

Flight testing will demonstrate that ICAAS system algorithms can be hosted on a testbed fighter aircraft and integrated with actual sensor derived target data while operating in realistic flight conditions. Capabilities to effectively handle simultaneous events needed to fight and win when outnumbered will be exercised. Complete encounters will be performed with the ICAAS testbed aircraft versus up to four aggressor aircraft, as depicted in figure 5.

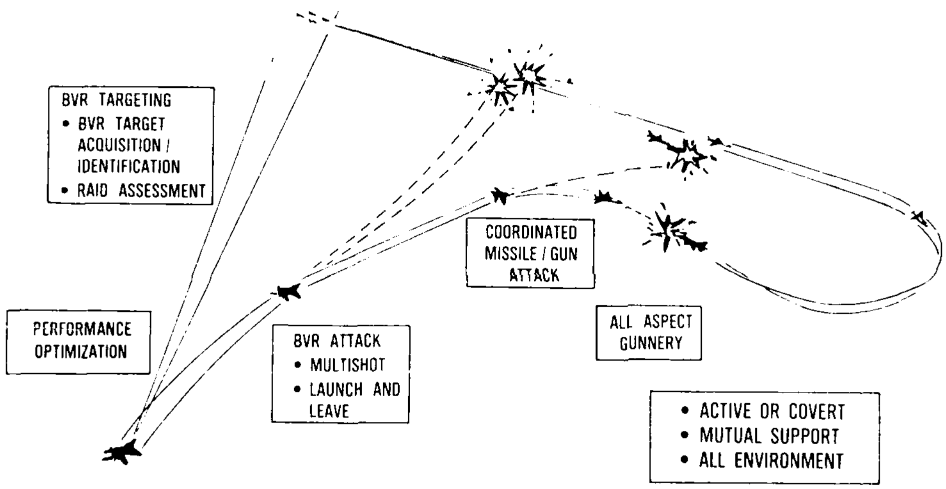

FIGURE 5

Engagements will be initiated at BVR and proceed through simulated weapon employments. Test conditions will be structured in a progressive buildup to examine full ICAAS design features and levels of automation. Initial testing will utilize an embedded Air Combat Engagement System (ACES) to provide onboard computer generated synthetic targets for verifying algorithms under controlled conditions. As described by Lt Brady (7), embedded scenarios are comparable to what the pilot would encounter in air combat maneuvering exercises. ACES is also expected to contribute to reduced cost of testing since target aircraft are not required, more encounters can be performed during each flight and an excellent software test capability resides in the system. Flight testing will then proceed using onboard sensor measurements of up to four aircraft acting as aggressors. A wingman aircraft will be internetted with the ICAAS testbed for a limited demonstration of two cooperative fighters versus four aggressor aircraft.

A special test not involving the ICAAS aircraft is envisioned for validation of the missile evasion capability. Missiles obviously cannot be fired at the ICAAS testbed. Therefore, a missile will be launched at a PQM-106 drone over a test range. Evasion algorithms hosted in the ground based range computers will determine control commands which will be transmitted to the drone. This will provide a direct demonstration of the capability to evade a threat homing missile which has been launched within "no escape" parameters.

Correlation of simulation and flight test results will receive special attention. Simulations will demonstrate the final or full-up ICAAS technology regardless of whether the actual equipment can be demonstrated in flight. Flight testing will provide selective validation of simulation results using components which can be flown during the program. The combined results of both types of testing are needed to achieve the best design trade-offs. If a disciplined system integration approach has been followed through this final step, then an effective ICAAS concept will result.

Summary

The ICAAS program will achieve significant technology advancements for fighter aircraft in the functions of attack management, flight management, and pilot/vehicle interface. These functions will individually provide combat performance improvements. Systematic integration of these functions, which is a primary goal of the ICAAS Program, will derive additional performance which would be otherwise unattainable.

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AFTI/F-16 - Impact of Cockpit Automation on Pilot Acceptance

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ABSTRACT

The Advanced Fighter Technology Integration (AFTI)/F-16 Joint Test Force recently completed a developmental flight test program investigating a fully automated weapons delivery system. The AFTI/F-16 boasted an impressive array of automatic systems that increased the effectiveness of both the pilot and airframe as an overall weapon system. The highly modified F-16 testbed was fitted with a digital flight control system, a conformally mounted infrared sensor/laser ranging pod, integrated fire/flight control computers, a digital color moving map, and a voice recognition system. The AFTI/F-16 integrated these sensors, avionics, and flight control systems into an Automated Maneuvering and Attack System (AMAS) capable of full authority automatic air-to-surface weapons delivery with profiles down to 200 feet (60 meters) above ground level. Long range target detection, lock-on, and tracking was accomplished by the forward looking infrared radar tracking pod. The pilot managed the system by identifying the target and commanding the sensor tracker system to track. With AMAS engaged, the pilot could alter the guidance solution or refine target track via hands-on controls. During ingress for an air-to-ground delivery he was aided by a low altitude radar autopilot. Target position was updated by laser range information and the advanced fire control computer. The only feature not automated was airspeed control. Cockpit management was aided by a fully integrated Voice Interactive Avionics (VIA) system capable of more than eighty functions covering communication, navigation, and sensor and weapon management. The VIA had the ability to recognize connected speech and generate synthesized warnings and advisories. The effects of this level of cockpit automation were studied for all phases of surface attack. This paper will present test results of the developmental flight test program and provide an assessment of the individual AMAS subsystems on the overall workload of the pilot and the pilot acceptance of a fully automated weapons delivery system.

ABBREVIATIONS

AFTI - Advanced Fighter Technology Integration
A/G - Air-to-Ground
AGL - Above Ground Level
AMAS - Automated Maneuvering Attack System
APPT - AMAS Pre-Planned Target
FCC - Fire Control Computer
FOV - Field of View
g - Acceleration Due to Gravity
GCAS - Ground Collision Avoidance System
HUD - Head-up Display
IFFC - Integrated Flight/Fire Control
IKP - Integrated Keyboard Panel
MDA - Minimum Descent Altitude
MFD - Multifunction Display
NWL - Non-Wings Level
OSB - Option Select Button
RALT - Radar Altimeter
STS - Sensor Tracker System
SWIM - System Wide Integrity Management
VIA - Voice Interactive Avionics
VPS - Vertical Planning Scale

INTRODUCTION

In today's high threat combat arena, the pilot with the best available technology has a clear advantage. For air-to-surface weapons employment, a very low altitude, high speed ingress, coupled with accurate weapon delivery and some capability to standoff from the target is a frequent tactical requirement. In today's combat environment of numerous weapons, multiple sensors, and extensive countermeasures, the key to success will be rapid assessment of available information and equally quick weapon employment. Thus, the interface of the pilot with these advanced technologies is of paramount importance.

The AFTI/F-16 Joint Test Force conducted a test program to develop a fully automated attack system for fighter aircraft between July 1984 and April 1987. This program was conducted at Edwards AFB, California and consisted of 237 flights and more than 347 flight hours. Testing was accomplished by seven pilots representing Air Force Systems Command, Tactical Air Command, and National Aeronautics and Space Administration. Flight test disciplines included flying qualities, avionics, weapons, and human factors evaluations.

One of the major objectives of the Automated Maneuvering Attack System (AMAS) phase of the AFTI/F-16 flight test program was to determine the level of pilot acceptance, adaptability, and workload associated with the automated low altitude weapons employment. This determination consisted of a large range of considerations, including a broad-based study of which flight control modes should be automated (and to what degree), examination of the overall contribution/distraction of each avionic subsystem, and detailed assessment of individual cockpit displays, controllers, and switches. Due to program delays and financial constraints, the air-to-ground automated attack was the only capability that was fully developed; therefore, that system alone will be the subject addressed in this paper.

TEST AIRCRAFT DESCRIPTION

The AFTI/F-16 (Figure 1) was a highly modified pre-production F-16 aircraft. The modifications included an asynchronous triplex digital flight control system which provided multiple task-tailored flight control laws (including decoupled aircraft motion). Twin canards were mounted on either side of the lower portion of the engine inlet. A fuselage dorsal fairing was added to provide internal space for avionics and instrumentation hardware. A forward-looking infrared laser sensor tracker system (STS) was mounted conformally in the right wing root with an aerodynamically similar "dummy pod" mounted in the left wing root. A radar altimeter (RALT) usable at all roll attitudes was installed in the forward fuselage. New and modified cockpit controls and displays included a sidestick controller, a linear motion throttle with a twist action for controlling AMAS functions, a wide field-of-view head-up display (HUD), and three multidisplay cathode ray tubes for system display and control. See Figure 2 for cockpit layout.

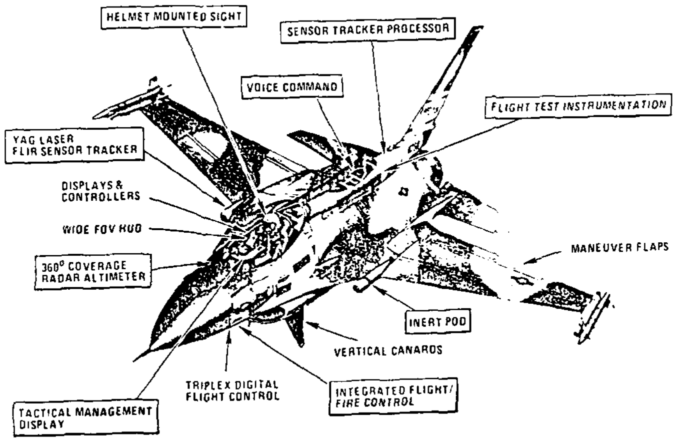


Figure 1 AFTI/F-16 AMAS Aircraft Configuration

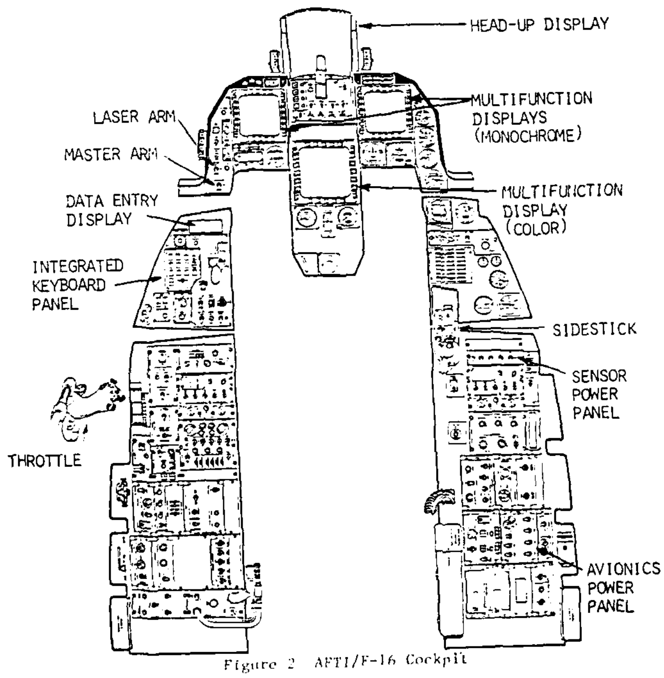


Figure 2 AFTI/F-16 Cockpit

The baseline avionics hardware and software for AMAS was Block 25 from the F-16C. The hardware was essentially unmodified and the software was highly modified to accomplish AMAS functions.

AUTOMATED MANEUVERING ATTACK SYSTEM

The overall goal of the AMAS installation was to maintain the weapon delivery accuracy of current bombing systems while increasing the survivability of the delivery platform in a high threat environment. This increased survivability dictated high speed, low altitude ingress and egress, and a significant "g" authority for the system during maneuvering and weapon delivery.

This tactical capability was developed in the AMAS phase of AFTI/F-16 testing through an automated bomb delivery system. The forward-looking infrared sensor and coaxial laser rangefinder were used for precise target location. Target position was then input to the integrated flight/fire control (IFFC) system to allow automatic lateral toss bomb deliveries. The complete automated delivery mode was called AMAS Pre-planned Target (APPT). The APPT attack could be separated into three distinct segments: ingress, curvilinear weapon delivery, and egress (Figure 3).

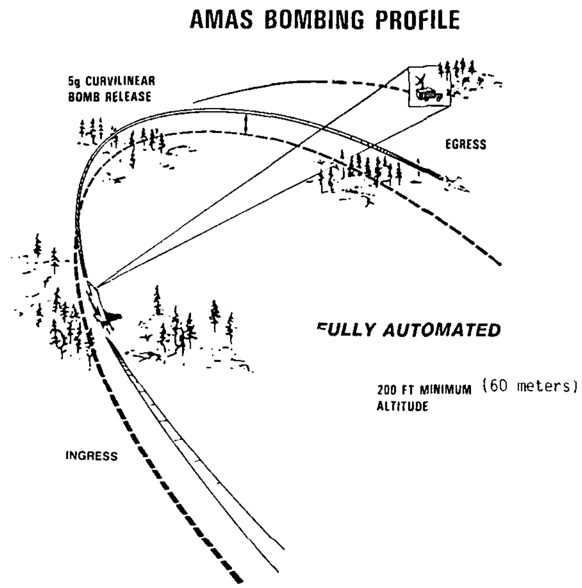


Figure 3 APPT Bombing Profile

The pilot input three parameters for the delivery. These were ingress altitude (the altitude above ground level at which the pilot engaged the system), the egress altitude (entered manually through a keyboard), and the desired bomb range (also a keyboard entry). The pilot controlled airspeed (with the throttle) throughout the delivery. All other parameters and inputs were controlled by the AMAS. The pilot could define the delivery profile through careful selection of the three input parameters and airspeed control. A given airspeed/altitude combination corresponds to a certain bomb range for a level release. If the pilot input that bomb range, the system delivered the bomb from an essentially level 5g turn. If the pilot selected a larger bomb range, the system would toss or loft the bomb; similarly, a smaller release range resulted in a diving delivery as shown in Figure 4. Real time adjustment of the desired bomb range was available to the pilot through throttle twist.

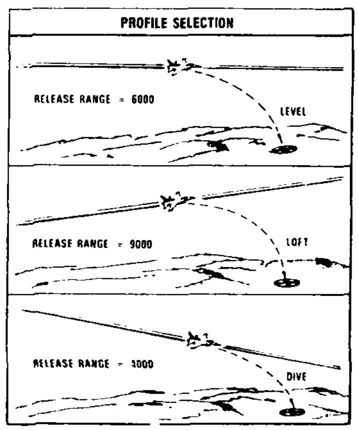


Figure 4 APPT Profile Determination: Level/Loft/Dive

Curvilinear APPT deliveries were successfully conducted from 200 feet (60 meters) to 2000 feet (600 meters) above ground level (AGL), at 1 to 5.2g's load factor, from 7 degrees of dive to 34 degrees of loft, with up to 115 degrees of bank angle. Airspeeds ranged from 440 to 560 knots true airspeed.

APPT PILOT ACCEPTANCE

Pilot acceptance of an automated maneuvering system with a 5g authority and 200 feet (60 meters) minimum altitude was by no means quickly or easily attained. The following quote is from a pilot's report

of the eighty-first test mission: "Trying to deliver an APPT bomb...the workload was so high on this flight that half the time it was impossible and the other half of the time it was more work than I had done in any other aircraft at any other time." This comment was from an experienced F-16 test pilot after his eleventh sortie in the AFTI/F-16. Yet only fourteen months later, another test pilot, comparing the automated system to manual deliveries, made the following comments after his second sortie in the aircraft: "Use of the automated APPT delivery mode greatly reduced pilot workload throughout the pass. Additionally, (it)...generated confidence in the system and allowed for a much less hurried ingress and attack." This complete change in pilot acceptance required significant improvements in three areas: pilot confidence in the system, aircraft flying qualities during APPT, and pilot interface with the system (particularly improvements in STS operation).

SYSTEM WIDE INTEGRITY MANAGEMENT

Pilot confidence in the AMAS was achieved through the development and test of an independent AMAS monitor called System Wide Integrity Management (SWIM). This not only provided artificial redundancy to the single strand avionics systems (such as the radar altimeter) but functioned as a ground collision avoidance system (GCAS) as well. Successful operation of both of these functions was necessary for the safe operation of the automated attack system at low altitude and high airspeed.

SWIM continually monitored the aircraft's flight path with respect to a pilot selected minimum ground clearance plane called the minimum descent altitude (MDA). If the system predicted that the MDA would be penetrated, it would first warn the pilot and then, if penetration was still imminent, fly the aircraft up. Pilot warning consisted of a verbal "pull up, pull up" and chevrons appearing in the HUD five seconds prior to flyup (Figure 5). As time to flyup decreased, the chevrons moved together. At flyup, the chevrons touched (forming a traditional "break X"); the pilot heard a tone and "fly up, fly up"; the aircraft automatically rolled to wings level and pulled 5g's until a 3 degree climb angle was achieved.

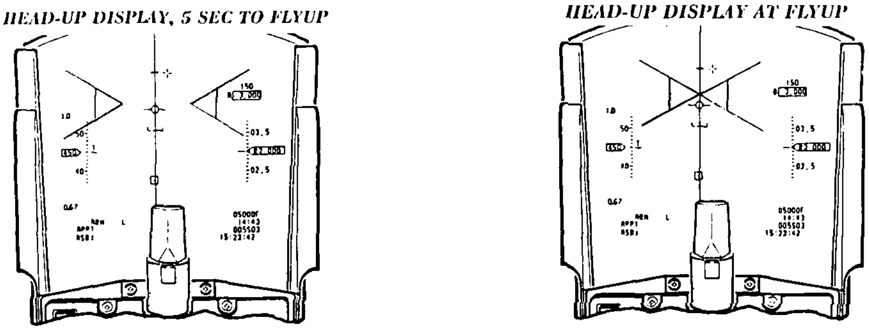


Figure 5 HUD Presentation for Flyup

The SWIM system would continually monitor avionic and flight control systems to ensure proper operation. If any of the systems were not fully functional, SWIM would prevent engagement of AMAS. If AMAS were already engaged, it would disengage the system and tell the pilot "you got it." If the failure occurred when the aircraft was within 500 feet (150 meters) of the MDA or within 5 seconds of flyup, SWIM would accomplish a flyup prior to system disengagement.

SWIM was successfully tested throughout the air-to-ground envelope. Load factors of -1 to +6g's, maximum roll rates, and airspeeds up to 550 knots were tested; 15 degrees of dive and 135 degrees of bank were tested to 150 feet (45 meters) AGL; higher dive and bank angles to 500 feet (150 meters). Successful completion of this testing was a large asset in building pilot confidence in safety of AMAS. Additionally, a SWIM validation was the first maneuver flown on any weapon delivery sortie, further increasing pilot confidence.

SWIM operated flawlessly throughout the flight test program. The only deficiency in the SWIM system was its use of only radar altimeter data for terrain clearance, with no forward looking capability. It was designed for level terrain use only (two percent terrain slope). During flight near the MDA, this tended to produce nuisance flyups when even small obstacles were overflown.

APPT FLYING QUALITIES

The AMAS had full authority for roll rates of 180 degrees/second, all bank angles, and -1 to 5g's in pitch. Additionally, up to 1g of direct sideforce could be generated through simultaneous deflection of the canards and rudder in a mode called "flat turn." This was the only air-to-ground decoupled motion used for AMAS. Altitude control was achieved through a low altitude radar autopilot, which would hold selected radar altitude by the use of bank angle/load factor. Pilot blending was allowed with AMAS engaged (i.e., pilot stick inputs above a certain threshold would be summed with automated commands).

The AMAS used this control authority in each of the three segments of the APPT attack. During ingress, the system flew the aircraft at the engagement altitude to a point offset from the target. This point lay on a sphere around the target defined by a 5g turn radius and the desired bomb release range (i.e., the aircraft would fly to a point where a 5g turn would be required to achieve bomb release at the desired range). System engagement too close to this imaginary sphere would result in a check turn away from the target before resuming the attack; engagement inside the sphere would result in the aircraft flying away

from the target and an automatic reattack. During the attack segment of the delivery, the aircraft would turn (nominally at 5g's) to align the bomb's velocity vector with the target at the selected release range. One half second after bomb release, the aircraft would enter the egress segment. The aircraft would roll to 135 degrees of bank and pull up to 5g's in slicing down to acquire the pre-selected egress altitude. It would then execute a 5g level turn at egress altitude until disengaged.

Pilot complaints while flight testing early ingress mechanizations were frequent. Problems with the pitch axis (normal load factor) centered on the ability of the autopilot to hold altitude, particularly during turns. Ingress steering used a maximum bank angle of 75 degrees; altitude control (even over rolling terrain) was achieved not by changing bank angle, but by varying normal load factor. This resulted in an aircraft motion variously described as bucking or heaving (the latter a particularly appropriate term). Load factor would vary by as much as ±1g. Roll onset rates caused many complaints; roll into a bank seemed abrupt, while the rollout on attack heading was very gradual. Additionally, the last few degrees of heading change (for ingress steering to the offset point) were achieved with flat turn as the wings were levelled. Flat turn (direct side force) was also used for small but seemingly instantaneous heading changes during target update. This apparently unpredictable use of side force was generally disliked by the pilots. Numerous different control mechanizations for the use of flat turn were tried, including changing control authority and when flat turn was implemented. No acceptable amount of flat turn was ever determined and pilot opinion finally prevailed. Starting with the 175th test flight, flat turn was made a pilot selectable option. Without exception, pilots then chose the control mode that did not use flat turn. This, however, was a mixed blessing; during ingress this mode frequently resulted in flight in a continuous small bank (whereas the flat turn mode was able to maintain wings level even for crosswind corrections).

The biggest flying qualities problem encountered with the attack segment itself was the transition from ingress to curvilinear or non wings level (NWL) steering. This transition was generally remarked upon as being "abrupt," although this improved somewhat as the program progressed. The most startling problem occurred, however, if the IFFC system perceived a discrete jump in aircraft state near the imaginary sphere delineating the ingress segment from the attack segment (e.g., a large target range magnitude jump near this border). The aircraft might, after having smoothly transitioned to the 5g NWL steering, decide it was really not yet to the sphere and transition back to a 1g ingress condition (followed shortly thereafter by another transition to 5g NWL steering). Needless to say, this certainly caught the pilot's attention at very low altitude. This problem was alleviated to some extent by increasing the reliability of the range inputs to the fire control computer. Additionally, adding some hysteresis to the range at which the aircraft transitioned to NWL steering smoothed this considerably. Prior to this change, as many as three mode changes in less than one second were occassionally seen during the transition (at which time SWIM disengaged AMAS).

The most frequent source of pilot interface problems during the delivery phase of APPT involved the mechanization of pilot blending. As mentioned earlier, pilot stick input (above a certain threshold level) would be summed with the automated flight control commands. It was the level of this threshold (breakout), that caused the most problems. Frequently during bomb delivery, the pilot would unknowingly input a significant amount of left roll stick (up to ten pounds (4.5 kilograms), certainly above the six pound (2.7 kilograms) breakout). These inadvertent pilot inputs would "corrupt" the APPT delivery, causing roll angle errors at bomb release: indeed, pilot inputs right at the breakout level would result in neither the pilot nor the flight control computers controlling roll. The cause of this inadvertent pilot-induced roll error was twofold. First, it was a human factors problem. The release consent (pickle) button was offset to the left of center on the control stick - holding the button down with the thumb during the delivery resulted in a left roll input. Second, it appeared to be a result of pilot apprehension during the low altitude attack maneuvering. This was indicated by the fact that little pilot induced roll error was experienced in the simulator, and during flight test, the severity of the problem increased as altitude decreased. It is noteworthy that a left stick input commanded a climb during our attacks (all deliveries were accomplished in right turns due to STS location in the right wing).

Pilots had three major complaints with the egress segment of the APPT manuever. The first was a sort of dichotomy in that although the egress maneuver itself was not as aggressive as most pilots would have flown it "hands on," the 5g, 135 degree slice back to the egress altitude was certainly violent enough to be uncomfortable (again, the roll-in seemed particularly abrupt). It then seemed to ease off too soon approaching the egress altitude, resulting in a gradual descent during the last few feet. This was not aggressive enough for combat maneuvering. The second complaint was more significant. On numerous occasions, the egress maneuver would pull down towards the ground hard enough to result in a flyup. While this was not a particularly frequent occurrence, pilots were not willing to accept an automated system that would satisfactorily perform a low altitude ingress and weapon delivery in a simulated high threat environment only to subsequently fly them up and expose them during egress. Finally, the endpoint of the egress maneuver (a 5g level turn upon reaching the egress altitude), while acceptable for flight test, was inappropriate for combat. Pilots agreed that egress to a preselected heading or steerpoint would be preferable.

SENSOR TRACKER PERFORMANCE

The final stumbling block to acceptable automated low altitude attack concerned the level of pilot workload during the delivery profile. Most workload was associated with the use of the infrared sensor tracker/laser range finder. Thus, successful integration of the STS into the system became a major concern. Weapon delivery on inertial target coordinates did not satisfy accuracy requirements; precise target state information was required for the fire control computer. This meant that the STS had to be able to support low altitude operation with the capability to acquire, lockon, track, and lase a target from far enough out to enable automated maneuvering to weapon release ranges of up to 20,000 feet.

Target acquisition was the first problem solved, but always required considerable pilot familiarity with the target area to ensure proper target identification. Early in the program the STS would present target video to the pilot at sufficient range to support bombing objectives. Suitable lockon and track capability, however, came much later. Pilots found it very frustrating to be able to locate the target in

the STS video, but not be able to achieve lockon. When lockon finally was achieved, it was frequently lost soon thereafter, a further source of pilot frustration. Lockon/track ability was enhanced by eliminating noise in the video, improving tracker gimbal stability, and improving tracking logic schemes. Providing better cue range and target height data to the STS enabled better ground stabilization of the video scene by reducing apparent target drift rates; this facilitated lockon by the pilot and enabled a quick relock if STS track were lost. These improvements allowed consistent STS track capability early enough in the run to enable use of the laser for target range update. This reduced time compression and workload for the pilot; it allowed him time to monitor aircraft altitude and airspeed, system performance, weapon system status, planned delivery profile, etc., increasing pilot situational awareness during the delivery. This breakthrough, occurring in late November of 1986, was a major change from earlier episodes of head-down operation wherein the pilot continually attempted STS lock and relock all the way through release. It significantly changed pilot perception of AMAS ease of operation, capability, and applicability.

These improvements in flying qualities during AMAS maneuvering, coupled with STS performance that supported accurate APPT weapon delivery with a tolerable pilot workload, backed with pilot confidence through SWIM, finally allowed the AMAS to achieve the payoff originally hypothesized for the automated system: improved weapon delivery capability for a high threat environment.

PILOT VEHICLE INTERFACE

In addition to the areas already discussed, pilot acceptance of the AMAS was closely tied to the pilot interface with the system. In this regard, the following areas will be discussed: cockpit controls (the stick, throttle, and multifunction displays), the cockpit displays (HUD, STS display, digital map) and one additional interface, voice interactive avionics.

HANDS-ON STICK AND THROTTLE

The AFTI/F-16 cockpit was designed for "hands-on" operation to the maximum extent possible. To this end, ten switches were located on the sidestick controller and eight more on the throttle. To increase the power of this arrangement, several of the switches had multiple functions, depending upon flight phase or maneuver (see Figure 6).

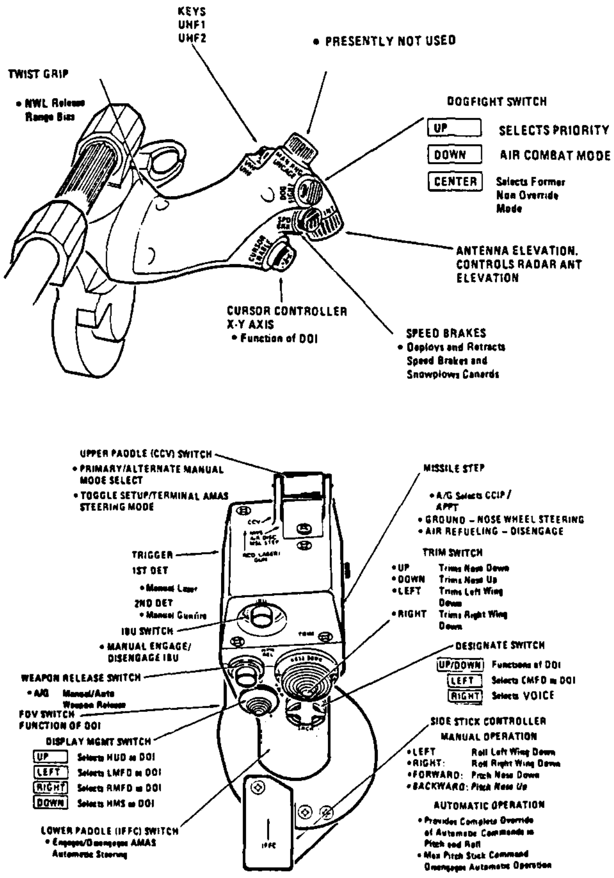


Figure 6 AFTI/F-16 Throttle and Stick

AMAS functions controlled on the stick included manual engagement/disengagement of the independent flight control backup mode, cockpit display management, engaging/disengaging IFFC, alternate mode selection (alternate flight control mode, execution of a less than 5g curvilinear delivery, execution of an alternate 1g wings level profile, reversion to curvilinear attack from wings level attack), laser consent, manual STS field of view changes, STS lock/break lock command, weapon release consent, and finally, flight path control through pilot blending. AMAS functions on the linear throttle included cursor control of STS aiming, release range adjustment through throttle twist, and airspeed control.

Needless to say, switch errors with the above arrangement with were not uncommon occurrences during the course of the flight test program--regardless of pilot experience. These errors ranged from merely embarrassing (transmitting on the wrong radio), to the annoying (entering a rotary requiring numerous switch actions for recovery), to serious (hitting the wrong paddle switch, thus inadvertently disengaging the system and aborting a test run), to potentially catastrophic (engaging the throttle cut-off instead of the twist grip release). The AFTI/F-16 certainly explored the limit of usable hardware on the stick and throttle.

The engagement/disengagement of the system through the lower paddle switch was straight-forward. The four different alternate mode selection functions of the upper paddle switch (which did not remain the same throughout the test program) were confusing and prone to pilot errors. Hands-on control of the sensor tracker evoked much pilot comment. STS field of view change capability on the stick was convenient, but the rotary involved (narrow-medium-wide-medium-narrow) was unwieldy. If the pilot was unsuccessful in locating the target in the narrow FOV, use of medium FOV then required four more switch actions to return to narrow FOV for lockon. STS aiming through the cursor control switch on the throttle was a continual problem. Maximum STS cursor input never had enough authority to rapidly slew the STS field of view to the target (or, until the target drift problem was solved, to keep the target in the FOV even if it were acquired); use of alternate cursor mechanizations for other slew rates through the HUD or radar cursor controllers proved unworkable since they corrupted target height or other data. Once the target was in the STS video, even the smallest possible cursor input seemed too large. This, coupled with a somewhat uncertain orientation of the axes of the cursor button due to its location on the side of the throttle, frequently resulted in "spiraling in" cursor inputs or pilot induced cursor oscillations until STS target lockon.

OTHER PILOT CONTROLS

Pilot inputs through the twenty option select buttons (OSBs) around each of the three multifunction displays (MFDs) and through the integrated keyboard panel (IKP) were generally perceived as being straightforward. The reduction in the overall number of switches by having the OSBs perform different functions (depending upon MFD format) was particularly appreciated. The MFDs were easily accessed with either hand; the IKP however, was located under the left canopy rail and obscured by the landing gear handle, making it inconvenient for inflight use.

The laser arm switch was located on the left armament panel above the master arm switch. While this was a convenient location, the switch was unfortunately similar in size and shape to the nearby master arm switch, causing confusion and switch errors. Additionally, the lever lock switch had two "arm" positions: down for manual arm (requiring pilot consent on the sidestick trigger for lasing) and up to auto for continuous lasing with STS lockon (a position never intentionally used due to the unreliability of STS lock). In attempting to safe the laser during the automated 5g egress maneuver, it was quite easy to go from manual arm through safe to auto, with the effect (continuous lasing) being quite the opposite from that intended. This was a major safety deficiency in the AFTI cockpit design.

HEAD-UP DISPLAY

Visual display of flight information was presented in a wide field-of-view HUD in the form of stroke-written symbols focused at infinity. The symbols represented information relating to navigation, attack, weapon aiming, and landing, including essential aircraft performance data (Figure 7).

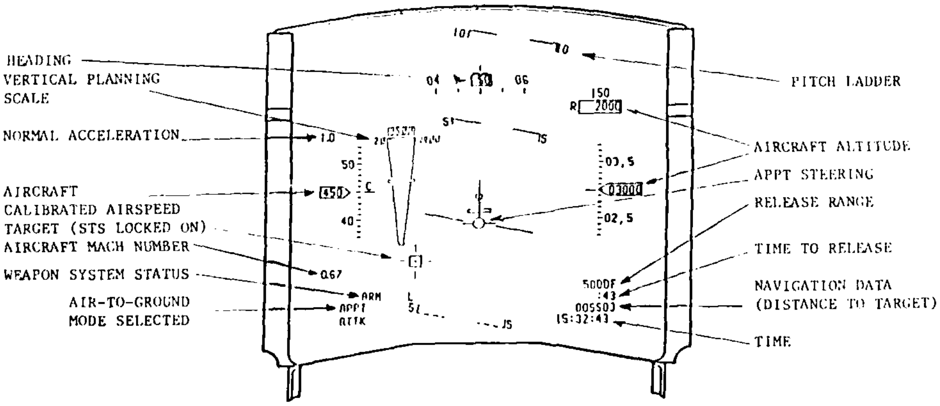


Figure 7 AFTI/F-16 Head-up Display

The AFTI HUD was equipped with digital readouts for airspeed, altitude, and heading, and increment marks for analog display of the same. The digital readouts were for instantaneous interpretation of

airspeed, altitude, and heading. The analog scales were presented for trend information during rapid changes in parameters. Airspeed was scaled in 25 knot increments and altitude was scaled in 250 feet (76 meters) increments. Pilots had difficulty in rapidly interpreting the scale increments and would have preferred smaller increments (10 knots and 100 feet (30 meters)) on the analog scales. The thermometer presentation of radar altitude was very useful in the low altitude environment. The analog presentations of the autopilot reference altitude and the MDA were convenient. This display would have been more useful if the radar altitude display would have been nonlinear (i.e., large scale increments at higher altitudes and smaller increments for precise altitude control at very low altitude).

One of the cockpit displays used during an AMAS air-to-ground delivery mode was the vertical planning scale (VPS) shown in Figure 8. The VPS was displayed in the HUD and provided the pilot with his predicted APPT delivery profile (climbing, descending, or level), anticipated release altitude, and maximum or minimum altitude. Pilots agreed with the VPS concept but did not like its mechanization. Some of the problems noted were: the VPS did not appear until late in the ingress maneuver (which left little time to adjust the delivery profile through pilot blending or release range changes); the VPS did not smoothly transition from lofting to diving deliveries during pilot blending or release range changes; the digital data was not found in the same location for different delivery profiles; and the display presentation was not easily interpreted.

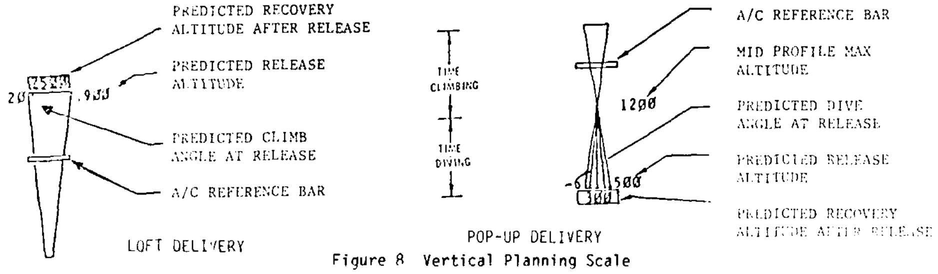


Figure 8 Vertical Planning Scale

MULTIFUNCTION DISPLAYS

In addition to the HUD, primary cockpit displays consisted of two monochromatic four inch (1.6 centimeter) cathode ray tubes and a five inch (2.0 centimeter) color tube called multifunction displays (due to the variety of formats available). Display capabilities ranged from built-in test, to flight control functions, to stores management, to sensor information (radar and STS). The cockpit setup of display format (primary and backup for each MFD) was pilot selectable for each flight mode; although time consuming during preflight procedures, it certainly was an asset during flight to have the cockpit customized to the pilot's personal preferences.

The MFD format of primary importance during an APPT weapon delivery was the sensor tracker page. In addition to target video, this display presented target range, laser and weapon status, and an artificial horizon (Figure 9). Early testing showed that pilots were much more comfortable with a "sky up" presentation of the target, as opposed to presenting it with respect to aircraft body axis coordinates. Major pilot complaints with STS mechanization concerned cursor control and FOV changes, as already discussed. Other complaints concerned poor video quality (requiring extensive pilot interpretation of the scene and background to confirm proper target identification) and the lack of any definitive means (such as a gray scale) to adjust video level and sensor gain prior to entering the target area. These deficiencies decreased probability of a successful "first pass" APPT delivery.

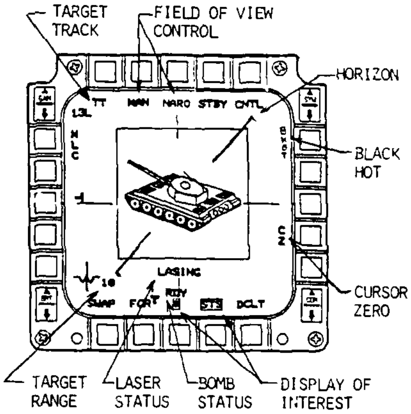


Figure 9 Sensor Tracker Page

The center MFD was a five inch (2.0 centimeter) color tube that could present a moving map, flight instrument displays, or flight control information. Unfortunately for the evaluation, the brightness and contrast of the center MFD were insufficient to support inflight use. This prevented comprehensive flight evaluation of the digital map and terrain data base incorporated into the system.

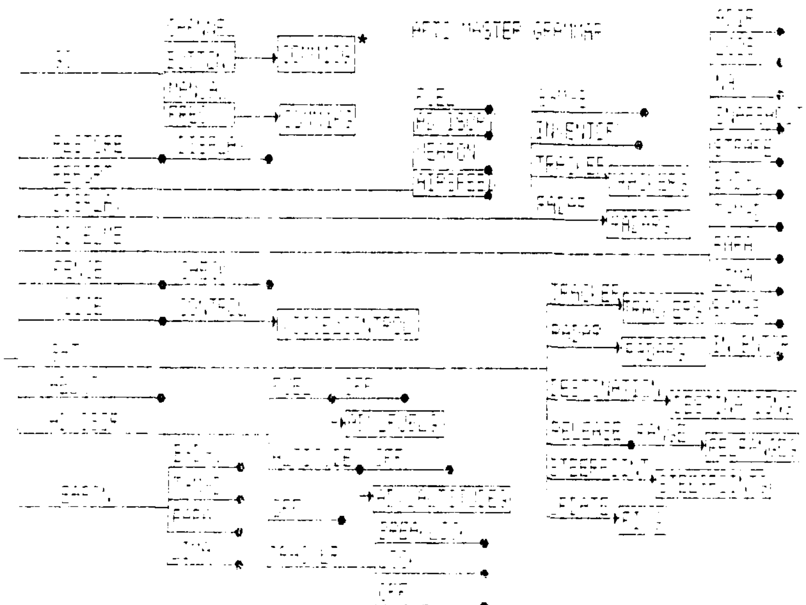
VOICE INTERACTIVE AVIONICS

The one pilot/vehicle interface that generated much interest was the use of voice interactive avionics (VIA). Certainly, in a single seat cockpit that had already approached the utility limits of displays and switches, an aircraft that could talk to the pilot and, more importantly, respond to verbal commands, seemed to be the ultimate answer. The voice interface between pilot and aircraft could be divided into two parts: synthesis and recognition/response.

Voice synthesis was provided for warning and caution annunciation; advisories for preset altitudes or fuel states were also available. Operation of these features was satisfactory. VIA response to pilot

voice inputs was also synthesized, providing feedback to the pilot for VIA activations.

Pilots could control communication, navigation, cockpit displays, weapon selection, sensor management, and check on aircraft parameters through the voice system. Three different VIA algorithms were tested. The first algorithm tested used a linear predictive coding scheme that used pattern matched words within a particular grammar. Once a match was made, the node within the grammar was switched to provide recognition of only valid phrases. Figure 10 presents a typical nodal structure used. This algorithm provided a connected speech capability. Testing of this algorithm was terminated early in the program due to software and hardware integration problems. The second algorithm was designed for isolated word recognition. It also used a nodal structure to increase recognition accuracy and decrease response time. It provided an audio "beep" as feedback to the pilot for successful word recognition. The majority of flight test results presented apply to this algorithm. The final algorithm used connected speech logic, looking at the entire phrase spoken for recognition. Extremely limited flight test of this algorithm was conducted due to its introduction at the end of the flight test program.



*NOTE: EACH OF THE NODES ENDING IN A "G" REPRESENTS ANOTHER GRAMMAR THAT COULD CONTAIN AS MANY AS TWENTY-ONE WORDS.

Figure 10 AFTI/F-16 Voice Nodal Structure

Use of the VIA system required extensive preparation and training, primarily to create a robust set of voice templates for individual pilot use. Templates were the data base the VIA system used for voice recognition. Template creation required initial enrollment of each of the 122 words of the VIA vocabulary, then "training" of the template, periodic update of the template, and template verification in the aircraft prior to flight. Although the VIA vocabulary was carefully selected to correspond as closely as possible to familiar pilot terminology, use of the VIA was not completely natural due to the nodal structure and syntax. Pilots agreed it was somewhat like learning a small foreign language.

Flight test of the systems progressed from benign flight conditions (1g level flight) to more demanding conditions (elevated load factor or high cockpit noise) to mission tasks (inflight refueling, air-to-air tracking, low level navigation and ground attack). The flight test results for the three pilots that extensively used the system are presented in Figure 11.

Pilot perception of recognition rates was worse than the test statistics show. Recognition rates presented rightfully show only errors or misrecognition by the VIA system and discount "pilot errors" due to improper utterances (being in the wrong grammar node, for example). The pilot, however, perceived that he had used voice to request some action by the aircraft that was not honored - a VIA deficiency. Additionally, recogniton rates were degraded by up to 50 percent for other than benign 1g flight condition (elevated g, high cockpit noise, etc.).

Overall pilot acceptance of the system was directly related to VIA recognition accuracy. All pilots realized a "learning curve" where recognition increased and then stabilized at a final value (about [illegible] percent). Pilots generally disliked the extensive preflight preparation required to use the voice system (enrollment, training, update, and verification). For the pilot with the best recognition rate ([illegible] percent) acceptance came wholeheartedly and he would readily use the VIA system for routine cockpit duties, even when not required by test objectives. For pilots with significantly lower recognition rates, use of the VIA came only reluctantly for fear of misrecognition or substitution.

Certainly the voice activation of aircraft functions will require higher recognition rates and more robust recognition templates for general pilot acceptance.

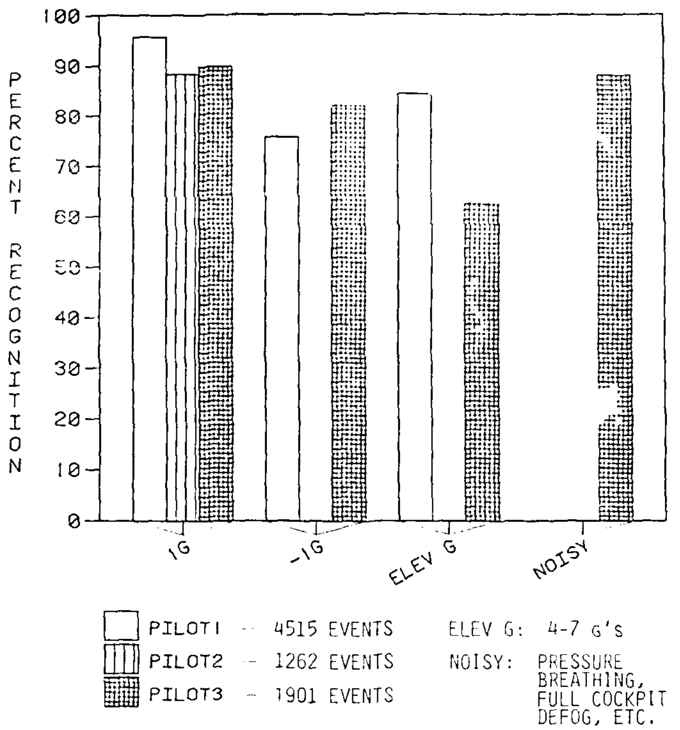


Figure 11 VIA Flight Test Results

SUMMARY

Pilot acceptance of an automated maneuvering surface attack system was achieved during the AFTI/F-16 AMAS flight test program. Automated attack with the final system configuration was preferred to manually flying the deliveries. Pilot confidence in the system was gained through system wide integrity management and its associated ground collision avoidance system. Improvements in aircraft flying qualities during automated maneu ring, and improved capability and interface of the infrared sensor tracker, ultimately allowed the pilot to satisfactorily accomplish coupled deliveries as low as 200 feet (60 meters) AGL.

Problems were identified with the pilot/vehicle interface of the system. The limit of usable hardware on the stick and throttle was reached. Deficiencies in the presentation of the curvilinear profile and parameters in the HUD were identified. Use of voice activation for aircraft and avionic functions was found to require better recognition rates for general pilot acceptance.

Overall, the AFTI/F-16 automated maneuvering attack system was found to provide an increase in aircraft weapon delivery capabilities.

ADVANCED HELICOPTER COCKPIT AND CONTROL CONFIGURATIONS FOR HELICOPTER COMBAT MISSION TASKS

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SUMMARY

Two piloted simulations were conducted by the U.S. Army Aeroflightdynamics Directorate to evaluate workload and helicopter-handling qualities requirements for single pilot operation in a combat Nap-of-the-Earth environment. The single-pilot advanced cockpit engineering simulation (SPACES) investigations were performed on the NASA Ames Vertical Motion Simulator, using the Advanced Digital Optical Control System control laws and an advanced concepts glass cockpit. The first simulation (SPACES I) compared single pilot to dual crewmember operation for the same flight tasks to determine differences between dual and single ratings, and to discover which control laws enabled adequate single-pilot helicopter operation. The SPACES II simulation concentrated on single-pilot operations and use of control laws thought to be viable candidates for single pilot operations workload. Measures detected significant differences between dual- and single-pilot operation and between single-pilot task segments. Control system configurations were task dependent, demonstrating the need for an inflight reconfigurable control system to match the optimal control system with the required task.

GLOSSARY

ADOCS advanced digital optical control system

AGL above ground level

ARTI advanced rotorcraft technology integration

ARMCOP Army copter

ASE aircraft survivability equipment

AT/AT attitude command/attitude stabilization (hold)

AT/VH attitude command/velocity hold

CGI computer generated imagery

CRT cathode ray tube

CSRDP crew station research and development program

E&S Evans and Sutherland

FPM flightpath management

HAC helicopter air combat

HQR handling quality rating

HUD head-up-display

KIAS knots indicated air speed

LHX light helicopter family

MM mission management

MMD mission management display

NASA National Aeronautics and Space Administration

NOE nap-of-the-Earth

OGE out of ground effect

RT/AT rate command/attitude stabilization (hold)

SPACES single pilot advanced cockpit engineering simulation

SWAT subjective workload analysis technique

TSD tactical situation display

UH-60 U.S. Army Utility Helicopter - 60 (Blackhawk)

VMS Vertical Motion Simulator

1. INTRODUCTION

The missions, tactics, and crew-task demands of the Army helicopter operations have undergone rapid and extensive change. One such change is the emphasis to fly only a few feet above the terrain and as close as possible to obstacles for maximum protection from perceived air defense threats. Given past technology, both pilot and co-pilot workload is high during NOE flight. For one pilot to perform both flightpath management and mission management, both tasks will have to be simplified or automated to achieve adequate performance.

The overall problem is to define aircraft stability, control, and performance characteristics, that when combined with the appropriate cockpit devices (e.g. integrated CRTs, helmet-mounted displays, touch-pads, voice input/output, moving map displays), allow adequate mission and flight performance. Several efforts have been underway to address these broad advanced rotorcraft issues such as the ARTI program (Ref. 1), the CSRDP (Ref. 2), development of the ADOCS (Ref. 3), and on-going work to rewrite the rotorcraft handling-qualities specification MIL-H-8501 (Ref. 4).

The SPACES experiments grew primarily from the desire to initiate the development of a single-pilot data base for the Army's LHX program. Previous handling-qualities specifications data and pilot compensation data were generated primarily in a two-crew context; that is, the evaluation pilot has been requested to perform only flightpath management tasks. A single-crew LHX pilot would have to simultaneously perform all the flightpath management tasks plus the mission management tasks previously performed by the co-pilot or other crew member, thus affecting performance.

SPACES I experiments were exploratory looking at 20 flight-control configurations in a single-pilot and a dual-pilot mode to help determine which combination(s) were most effective for tasks performed. The results from the first SPACES experiment are reported in Haworth, et al. (Refs. 5 and 6). The dual-pilot evaluations, with mission management tasks removed, served for baseline data collection and for comparison with single-pilot ratings during SPACES I. The SPACES II evaluation concentrated on single-pilot operation using the two best-rated systems from the SPACES I experiment and two additional control-response types. The two additional response types were thought to have potential for single-pilot operation based on flight tests for the proposed N8501 LHX Handling Qualities Specification (Ref. 7).

2. PURPOSE

The primary purpose of the SPACES effort was the investigation of single-pilot performance in the combat low-level and NOE flight environment using advanced rotorcraft cockpit and control law concepts. More specifically, these were investigations of the effects of adding mission management tasks to flightpath management tasks to simulate single-pilot operations in an advanced concepts cockpit.

3. FACILITY

3.1 Vertical Motion Simulator

The SPACES investigations were conducted in the NASA Ames VMS facility shown in Fig. 1. The simulator has a large-amplitude motion system with six degrees of freedom. The VMS is capable of large excursions in translational motion in two of the three axes (Z and either X or Y depending on cab alignment) and limited rotational motion. The pilot cab is mounted on a hexipod which provides the rotational motion and very limited translational motion. The pod is mounted to a carriage which is motorized and travels along the large horizontal beam. A rack and pinion gear system provides X or Y motion; and the large horizontal beam is moved in the Z direction by two large rams mounted under the beam.

3.2 Simulation Visual Model

The visual display consisted of a four-window CGI system (Fig. 2) utilizing the HAC data base (Ref. 8). The HAC data base with supporting CGI models provided moving visual ground and air threats for combat realism and forced task time lines. The primary visual ground threat was a ZSU-23-4 that was programmed to follow up to six paths through the data base. The ZSU-23-4 was also programmed to acquire and fire at the own ship (the piloted simulated helicopter) following acquisition logic when line of sight existed with the own ship. The visual air-to-air threat was a HIND-A helicopter that was modeled to fly multiple low-level flightpath routes.

In addition to threat/targets, special effects were added to the data base. Tracers were simulated when the gun was fired, a missile flash was simulated for missile launch, target hits were displayed, and air defense artillery bursts were simulated for visual indications of enemy fire. Own ship destruction from weapons firing was indicated by graphically drawn cracks on the HUD. Appropriate sound cues were coupled to the visual effects.

Visibility was reduced to 2 kilometers at the surface of the data base with a simulated cloud ceiling at 200 ft above the data-base floor. This simulated adverse weather, and forced low-level air-to-air engagements and operations. Wind and turbulence were also introduced during the simulation helping to demonstrate the usefulness of Earth-referenced stability systems for low-airspeed and hover tasks.

3.3. Advanced Glass Cockpit Hardware

The SPACES glass cockpit was designed to emulate a limited number of fundamental augmentation/automation concepts for advanced rotorcraft. Prior ADOCS experiments on automated/augmented control design and the design of an advanced concepts cockpit based on LHX/ARTI cockpit proposals served as the design framework and transition for the SPACES development. The physical cockpit design (Fig. 3) incorporated two CRTs and a HUD, programmable switches, touchscreens, data-entry device, voice output system, and side-arm flight controllers.

The HUD (an E&S Picture System One) was placed directly in front of the pilot. The HUD visually overlaid 90% of the center CGI CRT allowing the pilot to maintain visual contact outside the aircraft during low-level flight. Navigation, caution indicators, weapon status, and essential flight information were presented on the HUD for single-pilot operation. A line drawing of the aircraft and weapon stores remaining was shown on the lower part of the HUD.

The upper 13-in. CRT, called the TSD, shown in Fig. 4, presented a moving map display of the HAC data base and essential situational information. Map information included navigation routes, terrain features, cultural features, grid lines, and threat and friendly positions. An own-ship helicopter symbol was centered on the map and moved as the aircraft changed position and heading. Declutter features allowed the pilot to remove unwanted symbols and grid lines for detailed observations of desired map areas. A zoom feature allowed the pilot to zoom in and out from overhead as necessary for local area viewing. Line-of-sight indication was displayed on the moving map by use of a connecting red line between the threat and the own ship.

The lower 9-in. CRT, termed the MMD, was touch sensitive for pilot interaction. This display presented aircraft and weapon status, system menu items, situation reports, mission updates, and other needed text information. The interactive screen on the MMD was also used by the pilot to update waypoints on the TSD. In a degraded aircraft-system mode, the MMD displayed appropriate checklists for pilot action.

Other cockpit hardware included the programmable switches, voice output system, and data-entry keyboard. Twelve programmable micro-switches were situated around the TSD to supplement the menu selections found on the MMD and allowed for discrete activations of aircraft systems such as the landing gear, weapon systems, and aircraft survivability equipment. A voice recognizer and a personal speech system were planned for use for pilot-voice input/output interaction. Most of the reactive menu items found on the MMD were programmed to be selectable with use of the voice system, but technical difficulties and developmental time prevented use of the input system. Voice output from a Votrax provided voice warnings and caution messages along with checklist confirmation during routine and degraded operations. The data-entry device located near the left flight controller allowed for pilot-entered data-burst transmissions for tactical intelligence and mission updates.

Adjustable side-stick controllers were mounted on both sides of the pilot seat. The controller configuration for SPACES was a 2+1+1 limited-displacement controller setup (Fig. 5), patterned after the ADOCS Phase 2 configuration. The right-hand side-stick force controller was longitudinal and lateral cyclic control, and the left-hand side-stick force controller was collective. The force pedals with small displacement were used for directional control. A trim button was mounted on the top of the right hand controller during SPACES II for use with the attitude stabilization systems. A trigger release for gun firing and missile launch was mounted on the forward part of the right-hand grip. The left-hand controller, in addition to the action bar for collective activation, had two buttons and a proportional control switch on top of the grip. The upper-left button cycled the HUD configurations, the upper-right button was the switch to activate position control laws and the proportional switch was used to slew the missile pod up and down for targeting during SPACES II.

3.4. Mathematical Models

The mathematical model was the ARMCOP 10-degree-of-freedom helicopter model configured as a UH-60 (Refs. 9,10). The rotor model assumed rigid blades with rotor forces and moments radially integrated and summed about the azimuth. The fuselage aerodynamic model used a detailed model representation over a nominal angle of attack and sideslip range of ±15°. A simplified curve fit operated at large angles of attack or sideslip. Parameters from the UH-60 were used in the model along with developed stabilator control laws.

3.5. Advanced Digital Optical Control System

The flight control system used for the SPACES was the ADOCS design with only slight modifications. Basically the control system was a model-following system with feed-forward shaping and feedback. In the ADOCS nomenclature, the systems are referred to as command/stabilization but are thought of as command/hold by the research community. Two basic ADOCS control-response types were selected for SPACES I and four for SPACES II.

The basic control laws for the SPACES I investigation were the ADOCS hybrid control system (Table 1) and the ADOCS AT/AT for both the longitudinal and lateral axes. In addition to the two SCAS, the following selectable modes were available: 1) turn coordination, 2) heading rate command/heading hold, 3) altitude rate command/altitude hold, 4) airspeed hold (hybrid system only), and 5) position hold (hybrid system only). The vertical control system consisted of a vertical-acceleration command/vertical velocity-stabilization system. The yaw axis was a yaw-acceleration command/yaw-rate stabilization system for low-speed and forward flight. The flightpath control configurations for SPACES I are listed in Table 2.

SPACES II added two new concepts to the test matrix. The additions were an RT/AT system patterned after the ADOCS system, but with the hover hold/position hold added and a modification of the AT/AT system. The modified system was AT/AT in longitudinal and RT/AT in roll with hover hold/position hold added. The SPACES II configurations are summarized in Table 3.

4. *SUBJECTIVE DATA COLLECTION TECHNIQUES*

Three subjective ratings were used during the investigations: 1) The Cooper-Harper HQR scale (Ref. 11), 2) SWAT (Ref. 12), used as a technique to obtain workload ratings during the actual performance of a task, and 3) The Weighted Bipolar Rating Technique developed at the NASA Ames Research Center to record the multidimensional nature of mental workload (Ref. 13).

The SWAT and Bipolar workload data collection was performed to gather additional information that may have not been collected by use of the HQR scale itself. Additionally, the ratings were collected to determine the correlation between the three scales and usefulness of the scales as workload measures.

5. CONDUCT OF THE EXPERIMENT

5.1. General

Army engineering test pilots participated in the SPACES experiments. The pilots flew identical control configurations and performed the same flightpath management tasks in both the dual- and single-pilot role for SPACES I. An experienced Army aviator in the simulation control room montoring the cockpit and CGI visual, acted as the second crew member and conducted mission management functions (co-pilot duties) for the dual pilot setting for SPACES . The simulator pilot in the dual-pilot context operated as the flightpath manager maintaining flightpath control of the simulated vehicle similar to traditional handling qualities investigations.

Only the single-pilot operation was investigated in SPACES II. For single-pilot operation in both investigations, the simulation pilot was required to perform both flight path management and mission management tasks. This included flight maneuvering plus concurrent operation on a tactical communications network (Fig. 6), navigation, threat avoidance and countermeasures, selection of firing points, planning of engagement tactics, and weapons selection and firing.

5.2. Scenario

The basic mission scenario (Fig. 7) was to depart a forward refueling point and fly a series of waypoints (while evading threat detection and engagement) to arrive at a firing position, and then perform reconnaissance and subsequent air-to-ground attack tasks. After the ground engagement and damage assessment, the pilot was informed of a threat helicopter penetration which led to an air-to-air engagement with the threat helicopter. During these activities, the crew was also occupied with communications, navigation, reconnaissance, targeting, aircraft survivability equipment (ASE) and cther related mission management tasks.

Operation in the total scenario was approximately 20 minutes in length. Way points, threat aircraft routes, communications, and the threat laydown were varied at the end of each run to reduce learned responses for single pilot operation.

5.3. Data Collection

Data collection was divided into four scenario phases: 1) NOE low-level flight, 2) hovering reconnaissance, 3) air-to-ground attack, and 4) air-to-air engagement. The phases were designed to coincide with specific flight tasks maneuvers such as precision hover, bob-up and bob-down. Cooper-Harper HQRs and SWAT ratings were obtained from the pilot for the specified maneuvers at the completion of each scenario phase. Bipolar workload ratings were collected after all daily scenario phases were completed. Each of

the above scales are designed to measure pilot compensation and workload. Specific statistical information was obtained at the end of each scenario run.

6. RESULTS

The ratings obtained during dual-pilot operation signify performance of distinct flightpath management tasks. Ratings from single-pilot operation represent the result of imposing mission management tasks onto the flightpath management tasks. SWAT and bipolar ratings and figures are specifically contained in pilot-workload analysis section of this paper.

6.1. Nap-of-the-Earth/Low-Level Flight

For consistent task-measure comparison, dual-pilot ratings were gathered on a portion of a familiar low-level course where the pilot was instructed to maintain 60 ±5 KIAS and a variable altitude of 50 ft or less AGL. Single-pilot ratings were given for low-level flight routes at 60 ±5 KIAS while the pilot performed mission management tasks such as navigation, navigation update, communications, and use of threat countermeasures. Average single and dual pilot HQRs for selected ADOCS control systems for SPACES I and II are presented in Figs. 8, 9, and 10.

When comparing all dual-pilot and single-pilot HQRs obtained during SPACES I for NOE flight, the single-pilot ratings averaged 2.2 ratings worse than dual-pilot ratings overall, indicating degraded flightpath performance and higher pilot workload. Only configuration HB with AT/VH in pitch and RT/AT in roll received satisfactory handling qualities (HQRs less than 3.5 are considered satisfactory of Level 1) for single-pilot operation in the low-level environment. All 10 of the hybrid configurations flown "dual" received satisfactory ratings. Configuration HB was the best rated ADOCS hybrid system with altitude hold, and turn coordination in forward flight.

Altitude hold appeared to be significant for reducing workload and HQRs during the SPACES I studies. The altitude hold feature was common to the better rated configurations and served to reduce pilot compensation and workload by providing vertical terrain avoidance. It is predicted that terrain/obstacle avoidance in the lateral direction if implemented will most likely result in further reduction of workload.

For the SPACES II simulation, the same configuration as reported in SPACES I with AT/VH in pitch and RT/AT in roll received satisfactory (Level 1) average pilot ratings. For a similar system (AT/AT) without velocity hold in pitch but with RT/AT in roll, the average rating was Level 2, but close to the Level 1 limit. The configurations with RT/AT or AT/AT in both pitch and roll were solidly Level 2. This verifies results obtained in SPACES I that velocity hold is important for single-pilot NOE, low-level constant-airspeed flight modes. The same requirement does not exist for dual-pilot modes with the pilot acting only as the flightpath manager.

6.2. Air-to-Ground Engagement

The air-to-ground engagement occurred in hovering unmasked flight. In the dual-pilot situation, the pilot received and followed instructions from the co-pilot/researcher as to the attack position, target identification, azimuth pointing, selection of weapon, target acquisition, and when to fire. The single pilot performed the above tasks, including communications without the aid of a second crewmember. The specific targeting flight task was to maintain an unmasked hover altitude in line of sight of the ground target, slew in the direction of the target, overlay the HUD sighting reticle on the target within ±1° for 1 sec, and then maintain the target within ±3° of the reticle for an additional 2 sec. HUD symbology changes and audio tones indicated when lock-on and launch parameters were met. If line of sight existed with the ZSU-23-4 ground target for a specified amount of time after unmasking, the ownship was fired upon and hit resulting in forced time lines for target acquisition similar to real-world considerations.

For SPACES I (Fig. 11) the average differential in HQRs between single- and dual-pilot conditions were slightly more than one half of a rating point with the single-pilot condition being higher (degraded). This general trend probably reflected that the targeting task could not be completely off-loaded from the pilot in the dual-pilot situation, and/or that the given display features of the cockpit enabled the pilot to perform the task faster and better without the interference of verbal crewmember input. Three control configurations in SPACES I were rated satisfactory for dual-pilot operation in the air-to-ground attack task as presented in Fig. 11. These were configurations AG, AH, and HB with configuration HB receiving the best average HQR of 2.4. Each of the Level 1 dual-pilot configurations had two features in common: altitude hold and heading hold. Configuration HB was the only configuration that received average Level 1 ratings in both the dual-pilot and single-pilot conditions for the air-to-ground engagement task. The lowered ratings for the HB configuration were probably due in part to the position hold feature which is a element of that configuration. Since the ground-attack task for SPACES I was essentially one of bob-up and stabilizing on the target, the position hold feature was considered an enhancing feature.

The SPACES II air-to-ground attack maneuvers were generally more dynamic than SPACES I. In SPACES I the threat location on the moving map display was constantly updated and the pilot was able to plan firing locations. During SPACES II the threat location was not indicated on the moving map display until line of

sight existed with the threat. Once line of sight existed the pilot dynamically maneuvered to avoid acquisition and lock on while positioning to target the threat.

The results of the ground-attack phase for SPACES II are presented in Fig. 12. Only the RT/AT response-type received Level 1 average ratings. These results suggest that the attitude response-type (especially in combination with velocity hold) causes a degradation in handling qualities for the ground-attack task. Since the task involved precision pointing, the velocity hold function operated to readjust attitude to maintain groundspeed by commanding pitch and roll attitude changes, in direct opposition to the pilot's need for an attitude-stabilized platform. Both the AT/AT and RT/AT response-types produced attitude changes in direct proportion to cyclic commands, with some slight variation due to gust rejection with a good ability for precise pointing. The RT/AT was more attractive than AT/AT probably because of the requirements for larger control inputs to maneuver and the fact that a constant control force is not required to maintain the selected attitude with the RT/AT system.

6.3. Hovering Flight (Reconnaissance)

After the pilot completed the battle-damage reconnaissance of a specified target area he was required, while at a hover to send a data-burst transmission to update the tactical situation. This forced the pilot to maintain hovering flight and to respond to data-entry prompts on the TSD by using the keyboard near the pilot's left hand. During SPACES I only the ADOCS hybrid system with shown options for hover received acceptable or satisfactory ratings as shown in Fig. 13. The overwhelming option for favorable pilot comments was the position hold feature especially with wind and turbulence present.

One major conclusion of the SPACES I simulation was that the AT/AT response-type was unsatisfactory for the hovering task, while the AT/VH response-type, with position hold, was satisfactory (Level 1). There was no evaluation in SPACES I of an AT/AT response-type with position hold. For SPACES II, such a system was developed. In addition, the RT/AT case was evaluated both with and without position hold during SPACES II.

The position hold feature implemented on the ADOCS flight control system and evaluated during SPACES I was slightly modified for SPACES II: the range for engagement was increased from 3 knots to 5 knots groundspeed. In both simulations, position hold disengaged whenever the pilot applied more than one-half pound of force on the cyclic. When the pilot released the stick after the groundspeed was reduced below 5 knots, the position hold system would reengage. Figure 14 shows the influence of position hold on pilot ratings for the SPACES II hover task. It is evident that all of the response-types were solidly Level 2 when position hold was not available thus verifying the results from SPACES I. For precision hover, position hold is required for Level 1 HQRs in the single-pilot condition when mission tasking is imposed.

6.4. Air-to-Air Engagements

Air-to-air engagements were started from an OGE hover "ambush point." The air-to-air target was a threat helicopter that flew varying-programmed low-level routes, maneuvers, and airspeeds. The initial engagement was normally attempted with the simulated air-to-air missile. As the range to the air threat decreased, the pilot was allowed to select the fixed-gun system because of the increased maneuvering activity. The change over to the fixed gun system occurred when the pilot felt he could no longer obtain the necessary missile launch constraints (same as air-to-ground engagement). For dual-pilot simulations, the experimenter/co-pilot gave the pilot specific locations and tracking information for the threat helicopter until the air-to-air engagement became dynamic enough that the co-pilot was unable to aid the pilot. During single-pilot engagements, the pilot was only given the general location of the helicopter threat via ground and air communications, requiring the pilot to acquire the air target without the aid of a co-pilot.

During the SPACES I simulation, the average range for successful missile engagement was 2328 feet with average range for successful gun engagement approximately one half of that distance. Air-to-air engagements normally lasted less than 20 sec after establishing pilot line-of-sight with the target. Attitude command/attitude stabilization, configuration AH with heading hold and altitude hold (Fig. 15), was rated satisfactory for missile and gun engagements for both dual- and single-pilot conditions. When the hybrid configuration HA system was simulated, all pilots successfully engaged the threat helicopter with air-to-air missile system without reverting to the fixed gun even though this configuration received level 2 rating for the single-pilot condition. The average difference in HQRs, between single pilot and dual pilot, showed the single-pilot handling qualities being only slightly degraded. The air-to-air engagement task was primarily a single-pilot task, because of the required maneuver dynamics, targeting information presented on the pilot displays and short target-acquisition times. Once the air-to-air threat was presented, all other mission tasking was ignored while the pilots in both the dual- and single-pilot conditions concentrated on the target and HUD. For the SPACES II simulation, the results (Fig. 16) show that the RT/AT response-type was preferred by pilots over the attitude systems for the same reasons stated in the air-to-ground section of this paper.

6.5. Pilot Workload Analysis

Both SWAT and the NASA bipolar workload techniques revealed a higher level of pilot workload for the single-pilot configuration than the dual-pilot configurations as shown in Fig. 17. The techniques also distinguished between control configurations and showed differences between segments in the single-pilot

configuration. However, neither technique showed significant differences between segment tasks in the two-pilot arrangement. This indicated that the addition of a second crew member served to smooth out workload peaks and thereby reduced the differences between the workload of the flight segments. In reviewing the results and similarity between the SWAT and Bipolar subjective workload techniques, the correlation between the two is significant at $R = 0.67$. As expected both techniques were significantly correlated to the Cooper-Harper HQRs at $R = 0.75$ and $R = 0.79$, respectively for the Bipolar and SWAT.

Differences between dual- and single-pilot ratings on all scales were relatively small for both the air-to-air and air-to-ground engagements as found with the HQRs. The above tasks, although aided by the co-pilot/experimenter in the dual-pilot condition, were essentially single-pilot tasks because of the short time line for crew coordination, nature of the targeting task, and aovanced cockpit informational presentation that supplied visual targeting indications to the pilot.

7. CONCLUSIONS

7.1. General

As predicted, superimposing mission management tasks on flightpath management tasks result in degraded pilot HQRs and higher pilot compensation and workload. Because of the close proximity of obstructions in the low-level and NOE flight environment, constant flightpath supervision is required. The addition of mission management tasks further increases pilot attentional demands, contributing to operator overload and reduced flightpath performance. Handling quality rating, SWAT, and bipolar measures were sensitive to differences in pilot compensation and performance between the single-pilot and dual-pilot conditions and between single-pilot task segments. Significant differences did not exist between task segments in the dual-pilot condition since the addition of the second crewmember smoothed out work-load peaks.

7.2. *Nap-of-the-Earth/Low-Level Flight*

1) Airspeed hold was preferred over attitude hold in NOE/low-level flight. However, this probably reflected the task constraint requiring the pilots to maintain a constant airspeed for consistent task measure comparison. Holding constant airspeed is more reflective of low-level flight than of NOE dynamic maneuvering in which airspeed is constantly varied.

2) Altitude hold was also significant in reducing pilot compensation during NOE low-level flight. Altitude hold allowed the use of the pilot's left hand for mission tasks and provided limited vertical terrain avoidance, especially when the pilot was unable to constantly monitor altitude as a consequence of mission tasks. It is predicted that the addition of lateral terrain/obstacle avoidance system would further produce a reduction in piloting workload for NOE flight traveling.

3) The use of a rate command/attitude hold control response-type should be further investigated for use in the NOE maneuver environment where the pilot is not constrained by holding constant airspeed. Observations made during SPACES II indicated that rate command/attitude hold may be a preferable system for the NOE dynamic flight when combined with limited displacement side-arm flight controllers.

4) Attitude command/velocity hold in pitch, combined with rate command/attitude hold in roll for bank-angle hold was considered satisfactory for single-pilot low-level flight under the conditions tested.

5) Turn Coordination in forward fli[illegible] at 60 knots was also considered enhancing especially when combined with the rate command/attitu[illegible]ld in roll.

7.3. Air-to-Air and Air-to-Ground Engagements

1) For both air-to-air and air-to-ground engagements, the differences between dual- and single-pilot HQR, SWAT, and Bipolar ratings were relatively small, with single-pilot ratings slightly higher. Time lines were forced because the ground threat could destroy the own ship and because of the active presentation of the air threat. This caused the pilot to primarily pilot the vehicle and shed non-essential mission tasking to concentrate on destroying the threat.

2) Rate command/attitude hold was preferable over attitude command/attitude hold for low-speed precision pointing tasks for air-to-air and air-to-ground attack.

3) The air-to-air engagement was dynamic, lasting on the average of 20 sec. One of the greatest piloting challenges was to maintain aircraft alignment with the target to meet the constraints for missile launch. In the simulated low-level terrain environment targets were difficult to acquire at the longer ranges desired for missile launch. Missile engagements were further hampered when the pilot was required to identify the aircraft as friend or foe.

7.4. Hovering Flight

For precision hover, hover hold with position hold, which includes altitude and heading hold, is required for Level 1 single-pilot handling qualities. Addition of a second crew member has a similar effect as recorded during SPACES I. As in NOE flight, the close proximity of objects in the immediate environment drives the need for a precision hover capability. When the single pilot is required to

accomplish more than flightpath tasks the ability to maintain precision hover decreases, thus increasing the need for hovering flight stabilization.

7.5. Workload Analysis

The workload analysis showed that single-pilot workload was higher than dual pilot at the conditions tested. The SWAT and Bipolar workload techniques also distinguished between control configurations and showed significant differences between segments for the single-pilot case. The correlation between the two workload techniques was significant at $R = 0.67$. Both workload techniques were significantly correlated to the Cooper-Harper HQRs at $R = 0.75$ and 0.79, respectively, for bipolar and SWAT indicating the sensitivity of the handling qualities scale for measuring decreased task performance with increased workload.

A number of factors must be considered in weighing the importance of these conclusions:

1) The data comes from a moving, ground-based simulation. It is important that the results be verified in a flight-test program.

2) Hover hold as simulated was probably more accurate than current technology allows.

3) Pilot learning and transfer effects were predicted because of the complexity and unique tasking nature of the simulation. To counter the learning and transfer effect, a randomized block design was used. Randomization of conditions will increase data scatter; however, the measures of central tendency will remain valid. Since cognitive load tasking also influences the pilot ratings especially in the single-pilot situation, the pilot was not allowed to practice the same run several times prior to data collection. This caused the data as predicted to have more scatter when compared to typical handling-quality evaluations in which the same task configuration is practiced several times before a rating is obtained. The obtained performance rating in the SPACES conditions may be more typical of actual world performance and pilot compensation since the pilot has not recently practiced the same task.

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TABLE 1

ADOCS HYBRID CONTROL SYSTEM — SPACES I

LONGITUDINAL	PITCH ATTITUDE COMMAND/GROUNDSPEED STABILIZATION FOR LOW SPEED AND PITCH ATTITUDE COMMAND/AIRSPEED STABILIZATION AT HIGH SPEED. (AT/LV – AT/AS)
LATERAL	ROLL ATTITUDE COMMAND/GROUND SPEED STABILIZATION FOR LOW SPEED AND ROLL RATE COMMAND/ROLL ATTITUDE STABILIZATION AT HIGH SPEED. (AT/LV – RT/AT)
VERTICAL	VERTICAL ACCELERATION COMMAND/VERTICAL VELOCITY STABILIZATION FOR LOW SPEED AND FOR FORWARD FLIGHT.
YAW	YAW ACCELERATION COMMAND/YAW RATE STABILIZATION FOR LOW SPEED AND YAW ACCELERATION/YAW RATE FOR FORWARD FLIGHT.

TABLE 2

FLIGHT PATH CONTROL CONFIGURATIONS — SPACES I

CONFIGURATION	PITCH/ROLL		SELECTABLE SCAS MODES				
			B	C	D	E	F
	HYBRID	AT/AT	TURN COORD.	HEADING HOLD	ALTITUDE HOLD	AIRSPEED HOLD	POSITION HOLD
AA		X	X	X			
AB		X		X			
AC		X	X				
AD		X					
AE		X	X		X		
AF		X			X		
AG		X		X	X		
AH		X	X	X	X		
HA	X			X	X		
HB	X		X	X	X	X	X
HC	X		X		X	X	X
HD	X		X		X		
HE	X				X	X	X
HF	X			X			
HG	X			X		X	X
HH	X		X	X		X	X
HI	X		X			X	X
HJ	X						

TABLE 3

FLIGHT PATH CONTROL CONFIGURATIONS — SPACES II

VERTICAL SCAS
- RATE COMMAND/ALTITUDE HOL"

YAW SCAS
- YAW RATE COMMAND/HEADING HOLD

LONGITUDINAL AND LATERAL CONTROL SCAS

PITCH	ROLL	SELECTABLE SCAS MODES				
		TURN COORD.	HEADING HOLD	ALTITUDE HOLD	POSITION HOLD	AIRSPEED HOLD
HYBRID		X	X	X	X	X
AT/AT		X	X	X	O	O
AT/AT	RT/AT	X	X	X	X	O
RT/AT		X	X	X	X	O
*HYBRID - 1		–	O	X	w/o HH	–
*HYBRID - 2		–	X	X	O	–

*HOVER AND LOW SPEED ONLY

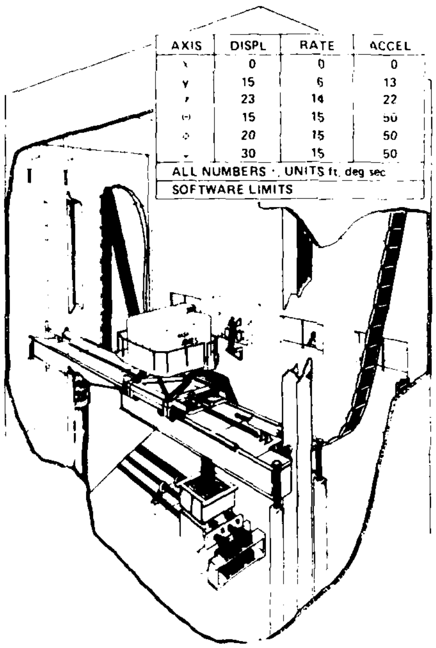

Fig. 1 Vertical motion simulator.

Fig. 2 Computer-generated image.

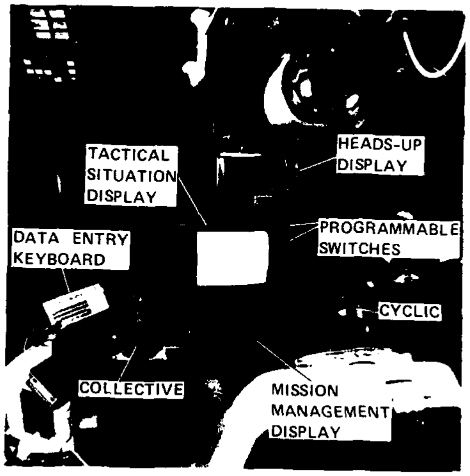

Fig. 3 SPACES cab.

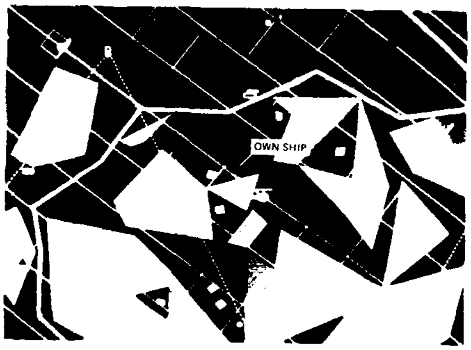

Fig. 4 Moving map display.

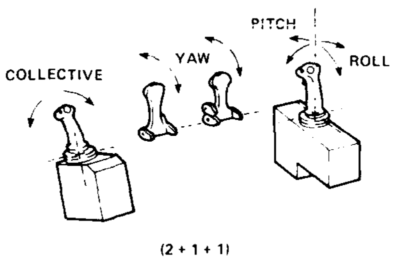

Fig. 5 Control configuration.

VOICE/COMM SCENARIO

PLAYER	CALL SIGN	VOICE	RADIO	FREQUENCIES
AIR BATTLE CAPTAIN	VN644A	1	VHF/UHF	122.9 243.5
BLUE 1	VN644A1	2	VHF/UHF	122.9 243.5
BLUE 2	VN644A2	–	VHF/UHF	122.9 243.5
OPERATIONS	VN644N	3	FM	33.7
GROUND COMMANDER	AN76B	4	FM	36.6
ARTILLERY UNIT	EB53D	5	FM	41.2
FAC	TA59C	6	VHF/UHF	135.3 246.8

SIMULATED COMMAND NET INTERFACE

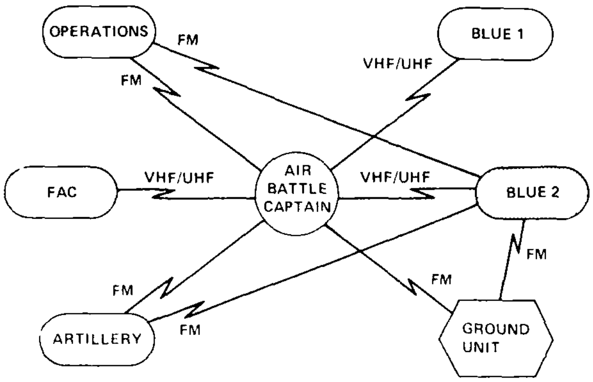

Fig. 6 Simulated command net interface and voice/command sceanrio.

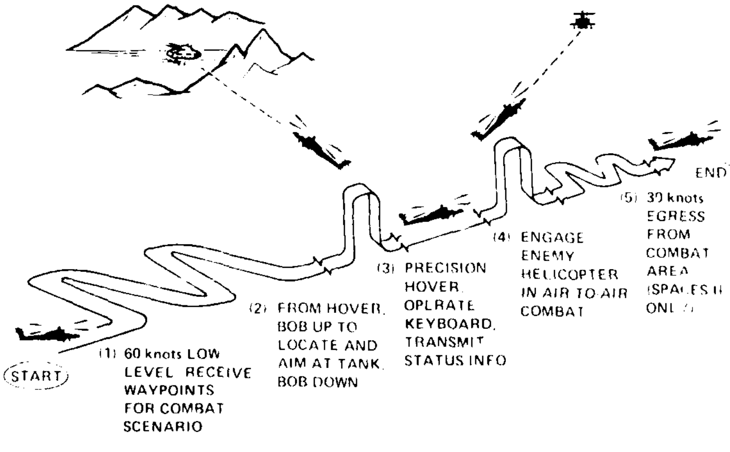

Fig. 7 Scenario and tasks for simulations. Breaks indicate pauses in simulation for Cooper-Harper and pilot workload ratings, and comments.

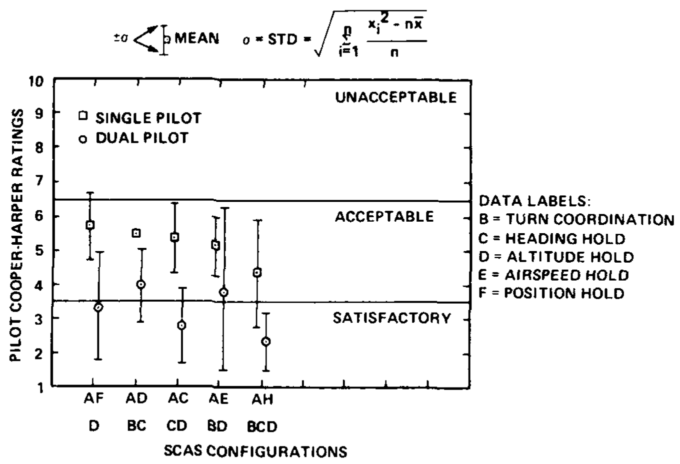

Fig. 8 SPACES I--NOE flight task at 60 KIAS: AT/AT control system.

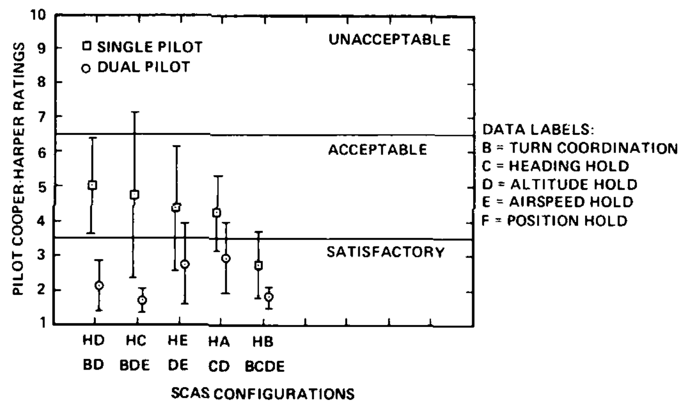

Fig. 9 SPACES I--NOE flight task at 60 KIAS: hybrid control system.

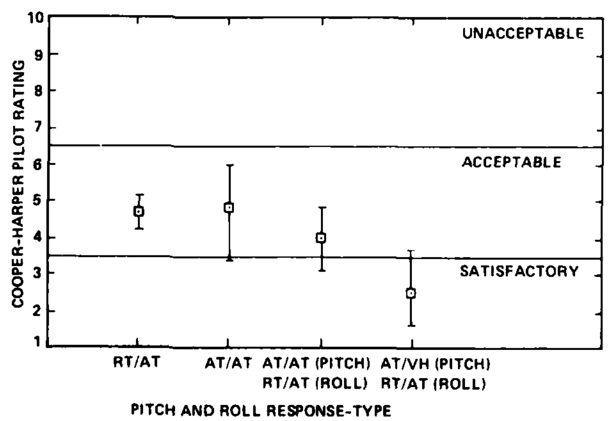

Fig. 10 SPACES II--NOE flight at 60 knots.

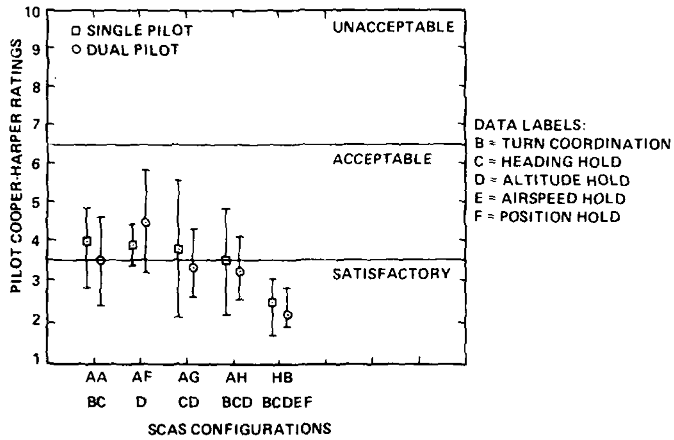

Fig. 11 SPACES I--Air-to-ground attack.

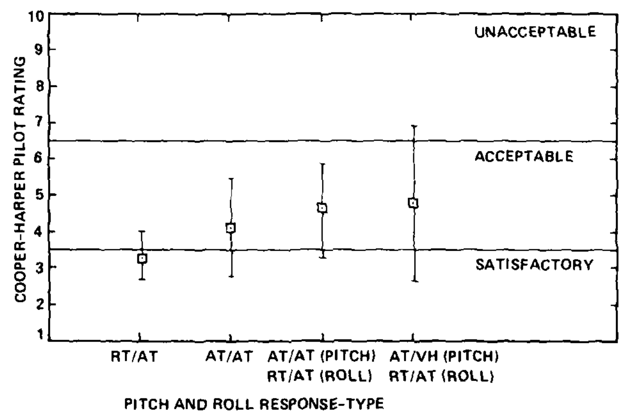

Fig. 12 SPACES II--Air-to-ground attack.

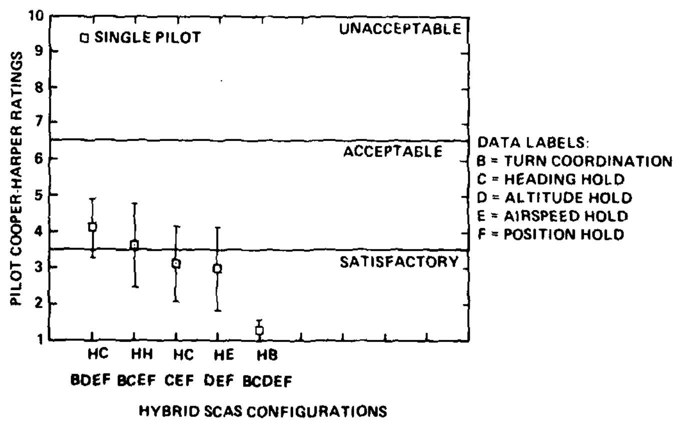

Fig. 13 SPACES I--Hover task with single pilot.

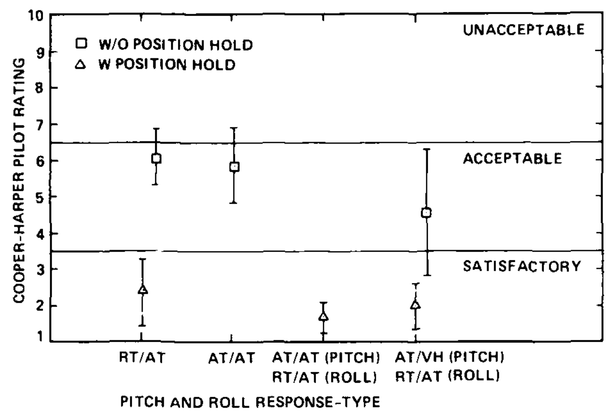

Fig. 14 SPACES II--Hover and transmit status report (single pilot).

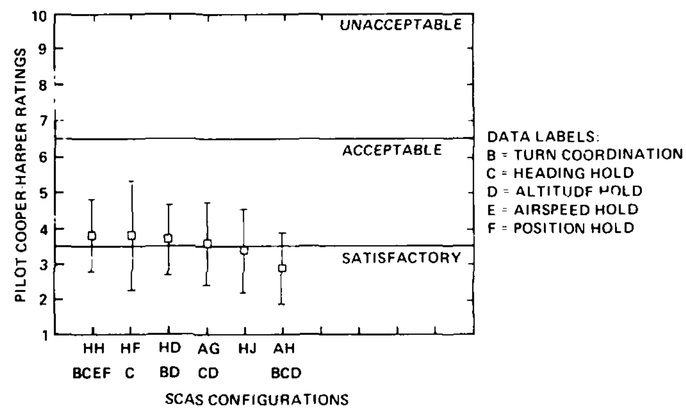

Fig. 15 SPACES I--Air-to-air engagement task.

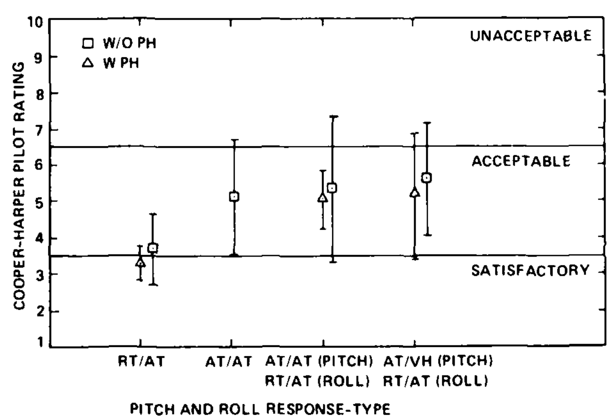

Fig. 16 SPACES II--Air-to-air attack.

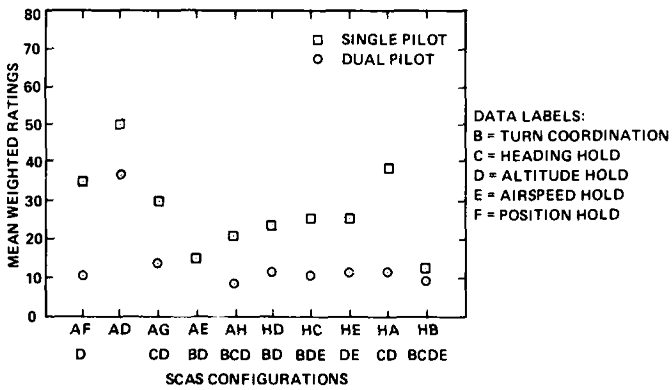

Fig. 17 SPACES I--NOE flight task (bipolar ratings): single and dual pilot.

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14. Abstract

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